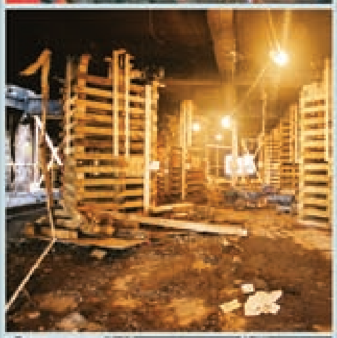
Stabilization of Buildings Workshop

August 25–27, 2009



Homeland Security

Science and Technology

US Army Corps of Engineers®
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FOREWORD

Because science and technology are crucial to mitigating natural and manmade effects on critical infrastructure and ensuring the continuity of their services, the U.S. Department of Homeland Security (DHS) Science and Technology (S&T) Directorate has established a goal to accelerate the delivery and understanding of enhanced technological capabilities. In support of this goal, the DHS S&T Infrastructure and Geophysical Division (IGD) is creating a program to investigate the enhancement of building stabilization after an improvised explosive device (IED) attack. To that end, the DHS S&T Directorate was pleased to sponsor the Stabilization of Buildings Workshop.

Through white paper discussions and breakout sessions, participants in the workshop explored topics such as monitoring and assessing buildings that are near failure, real-time decision making methods, first responder access during an emergency, and cost-effective stabilization techniques that could be implemented immediately following an IED attack.

The Stabilization of Buildings Workshop sought to:

- Discuss search and rescue issues facing first responders to the scene of the building attacked by an IED
- Explore hazard mitigation techniques for first responders
- Review case studies of building performance of buildings subjected to blast loads
- Investigate methods of monitoring and assessing the structural integrity of damaged structures
- Introduce innovative materials to be implemented in building stabilization
- Expose and learn of state of the art equipment, techniques, and strategies for stabilizing buildings
- Bring together private organizations, federal agencies, and universities to discuss research, techniques, and future needs for improving building resiliency against blast threats and protecting first responders

The results of this workshop will lead to a research agenda that S&T will use to help direct future efforts. These efforts will include creating a research clearing house, performing testing and simulation of advanced materials, and identifying deployable methods that can help to rapidly stabilize buildings after a terrorist attack. These efforts are anticipated to lead to a technology transfer to the private sector that will allow the rapid deployment of products to stabilize buildings after they have been impacted by IEDs.

These proceedings will consist of the workshop materials including the agenda, presentations, papers submitted, and presenter and author biographies. Also included are the workshop conclusions and discussion matrices that will be the basis of the research agenda on stabilization of buildings after an IED attack.

The Infrastructure and Geophysical Division of the U.S. Department of Homeland Security's Science and Technology Directorate would like to thank the U.S. Army Engineer Research and Development Center for the hosting of conference space and support.

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Acknowledgements

Many papers were submitted to the workshop committee for consideration as a result of the call for papers. All papers were reviewed by two independent reviewers. Some of the reviewing considerations were originality, completeness and suitability to the workshop goals. We acknowledge the efforts of the reviewers in this process. They provided expert technical opinions in a timely manner. Their efforts helped in ensuring a high quality papers and, ultimately, is helping this workshop to achieve its desired goals. These reviewers are:

- Stephen Cauffman, NIST
- Alexander (Alex) Cheng, University of Mississippi
- Lee Glascoe, Lawrence Livermore National Laboratory
- Jerome (Jerry) Lynch, University of Michigan
- Robert (Bob) Smilowitz, Weidlinger Associates
- Stanley (Stan) Woodson, US Army Engineer Research and Development Center

The Infrastructure and Geophysical Division of the U.S. Department of Homeland Security's Science and Technology Directorate would also like to express thanks to the Workshop committee for their diligent efforts in organizing and successfully carrying out this workshop. The committee is:

- Mila Kennett-Reston, Program Manager, DHS/S&T/IGD
- Eric Letvin, Project Manager and Facilitator, URS
- Mohammed Ettouney, Senior Technical Advisor and Coordinator, Weidlinger
- Stanley Woodson, Senior Technical Advisor and Coordinator, ERDC
- Gwendolyn Hall, Senior Advisor and Logistic Coordinator, URS
- Fernando Cortez-Lira, Systems Engineering and Technical Assistance Support, DHS/S&T/IGD
- Tate Jackson, Senior Engineer and Workshop Support, URS
- Laura Seitz, Workshop Support, URS

Biographic Sketches of Presenters and Authors

In Order of Agenda

Dr. Mary Ellen Hynes is the Director of Research for the Infrastructure/Geophysical Division in the Science & Technology Directorate (S&T) of the Department of Homeland Security (DHS). She comes to DHS/S&T after 30 years of research and development work at the US Army Engineer Research and Development Center headquartered in Vicksburg, MS. She obtained – with honors – her Bachelor's and Master's degrees in Civil Engineering from the Massachusetts Institute of Technology (MIT) and her PhD in Civil Engineering at University of California at Berkeley. Her past research areas focused on earthquake engineering for dams and probabilistic modeling. Now she has all the targets and all the threats for critical infrastructure protection and natural hazards.

Additionally, Dr. Hynes is the DHS/S&T Co-Chair of the National Science and Technology Council Infrastructure Subcommittee, co-chaired with the Office of Science and Technology Policy, Executive Office of the President. She is a member of the US-Japan Natural Resources Panel on Wind and Seismic Effects. Her technical affiliations include the American Society of Civil Engineers (past Chair of the Probabilistic and Risk Technical Committee and past Member of the Technical Advisory Council for the Geo-Institute; served on Geotechnical Journal editorial board), the Society of American Military Engineers, American Society for Testing and Materials (served on editorial board), International Society of Soil Mechanics and Foundation Engineers, and The Infrastructure Partnership (TISP). She chaired the National Science Foundation review panel for Geotechnical, Geomechanical, and Geoenvironmental Engineering for 5 years during the 1990's. She is the author or co-author of over 50 contributions to journals, books, proceedings and papers, and technical reports.

Blaine Brownell is an architect, sustainable building advisor, and researcher of innovative materials for architecture. He is the founder and director of the design/research firm Transstudio, and has taught at the University of Michigan and the University of Minnesota. Blaine is the author of Transmaterial: A Catalog of Materials that Redefine our Physical Environment, as well as Transmaterial 2, both published by Princeton Architectural Press. Blaine has practiced architecture in Tokyo, Nagoya, Houston, Seattle, and Minneapolis. His work has been published in A+U, Architectural Record, Architecture, BusinessWeek, Discover, Dwell, Fast Company, Forward, The Journal of Architectural Education, Materia, New Scientist, The New York Times, Popular Science, Sustainable Industries Journal, and the Seattle and Portland Daily Journals of Commerce, and he was featured as the cover story for the December 2006 issue of Architect magazine. His work has been exhibited at the Seattle Architectural Foundation, Center on Contemporary Art, and Consolidated Works in Seattle, as well as at DiverseWorks in Houston, the Taubman College of Architecture + Urban Planning at the University of Michigan, and the Centre Universitaire Méditerranéen in Nice. Blaine was selected for a 2006 "40 Under 40" award by Building Design & Construction magazine, and was the recipient of a Fulbright fellowship to Japan for 2006-2007, during which time he researched contemporary Japanese material innovations at the Tokyo University of Science.

Dr. Amar Chaker obtained a Ph. D. degree in Civil Engineering from the University of Illinois at Urbana-Champaign and a degree of 'Ingénieur Civil' from 'Ecole Nationale des Ponts et Chaussées', Paris, France.

He has held faculty positions at the University of Illinois at Urbana-Champaign and Drexel University. He has served as Professor and Director of the Civil Engineering Institute of the University of Science and Technology of Algiers, Algeria. As Technical Director of the Algerian State Organization for Technical Control of Building Construction, he co-chaired the Committee for the Algerian Earthquake-Resistant Design Code and participated in several major post-earthquake investigations and in a seismic hazard evaluation and urban seismic microzonation study for the region of El Asnam, Algeria.

He joined ASCE in 1999 where he has worked in Technical Activities, the Transportation and Development Institute, the Civil Engineering Research Foundation, and the Building Security Council. He is now Director of the Architectural Engineering and Engineering Mechanics Institutes of ASCE.

He served as a member of the Advisory Editorial Board of Earthquake Engineering and Structural Dynamics, and of the Editorial Board of *Annales Maghrébines de l'Ingénieur*. He was a Founding Member and President of the Algerian Earthquake Engineering Association. He is a member of ASCE and EERI, is active in several technical committees, and is author or co-author of over 50 publications.

Dr. Paul Mlakar is the Senior Research Scientist for weapons effects and structural dynamics at the U.S. Army Engineer Research and Development Center (ERDC). He was recently a key member of the Interagency Performance Evaluation Taskforce that studied the behavior of the New Orleans hurricane protection infrastructure in Katrina. Following the September 11 airliner crash into the Pentagon, Dr. Mlakar was selected by the American Society of Civil Engineers (ASCE) to lead a study of the structural behavior.

From 2000 to 2003 Dr. Mlakar was the Technical Director of the ERDC responsible for innovations in military engineering to rapidly upgrade transportation infrastructure and assure cross country mobility. From 1995 to 2000 he served as the Chief of the Concrete and Materials Division of the U.S. Army Engineer Waterways Experiment Station (WES). In the winter of 1996, Dr. Mlakar acted as the Chief Engineer of a North Atlantic Treaty Organization Task Force that rapidly restored a war-damaged century-old bridge on the main line of supply for Operation Joint Endeavor in Bosnia.

From 1984 to 1995 Dr. Mlakar founded and guided the Structures Division of JAYCOR as a Vice President. This work included the invention of a patented hardened air cargo container capable of resisting the effects of internal explosions. Other projects involved the design of structures to resist explosive effects including the protection of embassies and other visible targets against terrorist bombings. Dr. Mlakar also served on the ASCE team that assessed the structural performance of the Murrah Building in the 1995 Oklahoma City terrorist bombing.

As a research engineer for the WES, from 1973 to 1984, Dr. Mlakar was the contributing leader of a team that investigated the mechanics of structural elements. Projects included the seismic response of hydraulic structures, the behavior of field fortifications subjected to weapons effects, and the application of probability to structural design. During the period 1966 to 1973, Dr. Mlakar was an officer in the Corps of Engineers. This encompassed a faculty assignment at the U.S. Military Academy (USMA) at West Point, as well as troop command and staff service in Vietnam and the U.S.

Dr. Mlakar graduated from USMA and subsequently earned an M.S. and a Ph.D. in Engineering Science from Purdue University. He is a registered professional engineer and the author of some 150 technical publications. Dr. Mlakar is a Fellow of ASCE and the past Chair of its Committee on Critical Infrastructure. He is also active in the American Concrete Institute and the Society of American Military Engineers. Dr. Mlakar has received a number of prestigious honors including the 2003 ASCE Forensic Engineering Award and the 2004 Purdue Alumni Achievement Award.

Stephen Cauffman is currently the Deputy Division Chief of the Materials and Construction Research Division. He co-leads the Strategic Goal on Disaster Resilient Structures and Communities and manages the Measurement Science for Structural Performance under Multi-Hazards Program. Prior to this, he was the Leader of the Structures Group. Mr. Cauffman led the team that conducted reconnaissance of the performance physical structures in Hurricanes Katrina and Rita in 2005. Mr. Cauffman was the program manager for the Federal Building and Fire Safety Investigation of the World Trade Center Disaster. His work at NIST has included coordination of the Interagency Committee on Seismic Safety in Construction (ICSSC) as its Technical Secretariat. Mr. Cauffman also serves as Technical Secretariat for the U.S.-side panel of the U.S.-Japan Joint Panel on Wind and Seismic Effects (UJNR). He was the technical point of contact for the Partnership for Advancing Technology in Housing Cooperative Research Program. Mr. Cauffman also has provided support to the Advanced Technology Program in outreach to the construction materials industry.

Prior to joining NIST, Mr. Cauffman was a Senior Program Manager with the Civil Engineering Research Foundation (CERF). In that capacity, he was responsible for conducting studies related to advanced technology for the construction industry. Mr. Cauffman also served as Secretariat to the High-Performance CONstruction MATerials and Systems (CONMAT) Council, an industry/government group dedicated to promoting research, development, and deployment of advanced construction materials. Working with CONMAT and NIST, Mr. Cauffman developed an industry plan for participation in the Advanced Technology Program (ATP) and conducted workshops to educate industry on ATP.

Mr. Cauffman's experience includes 11 1/2 years with the Atlantic Research Corporation. He was a Program Manager with the Solid Propulsion Division, leading efforts to develop main and divert propulsion systems for a small interceptor missile and gas generator-based fire suppression systems. Mr. Cauffman also was a Program Manager in the Advanced Materials Division, where he was responsible for programs to develop composite aerospace and marine structures. His experience at the Atlantic Research Corporation also included thermo-mechanical and thermo-physical testing and characterization of advanced carbon-carbon, metal-matrix, ceramic-matrix, and polymer-matrix composites. Mr. Cauffman received a Bachelor of Science in Physics from George Mason University.

Dr. H.S. Lew is Senior Research Engineer at the National Institute of Standards and Technology. He carries out a broad range of research programs in the fields of structural, earthquake and materials engineering. He was Chief of the Structures Division (1989-1999). Prior to joining NIST, he was an assistant professor at the University of Texas at Austin.

Dr. Lew is a fellow of the American Society of Civil Engineers (ASCE) and the American Concrete Institute (ACI) and a member of the National Academy of Engineering of Korea. Dr. Lew has served on the Board of Direction (1987-1990) and the Technical Activities Committee (1989-1995) of the American Concrete Institute, on the Board of the Building Seismic Safety Council (1998-2004) of the National Institute of Building Sciences, and was a member of the Board of Governors of the ASCE/Structural Engineering Institute.

Dr. Lew serves on various technical and administrative committees of national and international organizations. He is a member of the ACI Building Code Committee (ACI 318). He served on the American Institute of Steel Construction’s Committee on Design Specification for Steel Buildings (AISC Specifications Committee), and on the Seismic Provisions Committee of the Building Seismic Safety Council. Dr. Lew has published over 150 articles, papers and reports on performance of structures, construction safety, and failure investigations of structures.

Dr. Lew is the recipient of several honors and awards, including: the ACI Wason Medal for "Materials Research" in 1980 and for "the Most Meritorious Paper in Research" in 1987. He received the ACI Kennedy Medal in 1990, and the ACI Turner Medal in 1999. He received the 2005 ASCE/SEI Walter P. Moore, Jr. Award for his technical excellence in the development of standards. He is a recipient of the U.S. Department of Commerce Silver Medal in 1982 and 2001 and Gold Medal for distinguished achievement in Federal service in 2005. He was the U.S. Federal Government "Engineer of the Year" in 1995.

Dr. Lew is a registered professional engineer in Washington D.C., and the States of Maryland and New York. He received his B.S. in Architectural Engineering from Washington University, his M.S. in Civil Engineering at Lehigh University, and his Ph.D. in Civil Engineering at University of Texas.

David J Hammond, SE graduated from the University of California, Berkeley in 1954 with a B.S.C.E., and was engaged in the design of seismically resistant structures in the San Francisco Bay Area from 1957 to 2000. He served in the U.S. Army from Jan 1955 to Jan 1957, and was stationed at Ft. Belvoir in the spring of 1955. While serving in the Army he began his instructional career as a Troop Information & Education NCO. In 1985, he began his involvement in Urban Search and Rescue as the leader of the U.S. Search Dog Team 3 at the Mexico City Earthquake. Since that time, David has continued as a support member of California Rescue Dog Association in numerous other disasters.

David was an original member of the FEMA US&R Advisory Committee and is the current Chair of the DHS/FEMA US&R Structures Sub-group. He is a lead instructor for the USACE-DHS/FEMA Structural Specialists (StS) training program, as well as other FEMA US&R training courses. He was a lead StS for the FEMA response to the Oklahoma City Bombing incident, the Puerto Rico Gas Explosion in 1996, and the World Trade Center Collapse in 2001. As member of the FEMA US&R White Incident Support Team (IST) he has responded to many hurricanes. He is a member of DHS/FEMA's CA-TF-3 located in Menlo Park, California.

John Osteraas, Ph.D., P.E. is a Group VP and Principal Engineer at Exponent Failure Analysis Associates in Menlo Park, Ca. He received his BSCE from the University of Wisconsin – Madison in 1976, and his Masters of Science and PhD from Stanford in 1977 and 1999, respectively. John has been involved with the US&R Program since the early '90s, first as a reviewer of David Hammond's original StS training materials, then as a Structures Specialist (StS) with DHS/FEMA's CA-TF3 in Menlo Park, California. He deployed with CA-TF3 to Hurricane Iniki in 1992 and to the Northridge Earthquake in 1994. In 1995 he relieved David Hammond as lead StS at the Oklahoma City Bombing response. As a member of the DHS/FEMA US&R Incident Support Team, John was deployed to the World Trade Center response in 2001, the Salt Lake City Olympics (Operation Olympic Watch) in 2002, the Democratic National Convention and Hurricane Frances in 2004, and Hurricane Katrina in New Orleans in 2005.

Alan D. Fisher, P.E. is Manager of the Construction Design Group for Cianbro Corporation in Portland, Maine. He is responsible for the engineering of all types of temporary structures used during the construction of large civil-structural projects. Past assignments have included the design of major cofferdams, steel erection plans for major bridges, and jacking of loads to 3000 tons. Most recently he managed the construction design efforts for the installation of supplemental main cables for a suspension bridge, a first in the US. Alan is a member of the Transportation Research Board (TRB) Strategic Highway Research Program 2, and ASCE's "Load on Structures during Construction" Committee. Alan is a member of the National Council of Examiners for Engineering and Surveying committee for exam question writing for construction.

Alan has been involved with the DHS/FEMA Urban Search and Rescue (US&R) National Response System since 1993, starting as a Structures Specialist with MA-TF1. He has deployed with MA-TF1 to the Atlanta Olympics in 1996 as a Planning Team Manager, to the Worcester Fire Recovery in 1999 as the lead Structural Specialist, and to the World Trade Center Response in 2001 as a Planning Team Manager. He has served on the DHS/FEMA US&R Structures Sub-group (formerly the Technical Sub comm.) since 1997. Alan is actively involved as a lead instructor for the US Army Corps of Engineers US&R Structures Specialist training program.

Tom Niedernhofer, PE has worked as a structural engineer with the Corps of Engineers for 18 years in St. Louis, Mo., and then in California since 2002. Prior to June 1986 he worked as a building design and project engineer for Jenkins and Charland, Inc., a structural engineering firm in Florida.

Tom's interest in US&R began while being deployed to perform structural building assessment after the Loma Prieta earthquake in 1989. Tom completed the USACE/FEMA pilot Structures Specialist training class in 1992, and has assisted with shoring instruction at every StS training class since. Currently he is the Program Manager for the US Army Corps of Engineers US&R Program, located in the Bay Area. Tom has deployed to Hurricane Andrew, the Northridge Earthquake, the Oklahoma City Bombing, to the World Trade Center, and local rescue responses. He has deployed to "Operation Olympic Watch" in 2002, Bulgaria in 2003, and Uzbekistan in 2003 for US&R training and mobilization exercises. His US&R training support also reaches to the military regarding operations and exercises.

Bil G. Hawkins, P.E. has been a Structures Specialist with NM-TF1 (New Mexico), CA-TF7 (Sacramento) and the US Army Corps of Engineers (USACE). He is currently a Structure Specialist with CO-TF1 (Colorado) and member of Park County Wilderness Search and Rescue. He is also a volunteer firefighter with Elk Creek Fire and Rescue near his home in the mountains west of Denver, Colorado. He is SPRAT Level III and IRATA Level II certified as a rope access technician leading teams on complex bridge and building inspections. He is the Director of Structural Engineering and a Principal of Knott Laboratory, a nationally recognized forensic engineering firm located in Denver, Colorado.

Bil was on the first team of USACE engineers to deploy to Iraq at the onset of Operation Iraqi Freedom and spent 8-months in theater including 10-days as an advisor on the Bingol, Turkey earthquake in May 2003. Other USACE deployments include Hurricane Katrina, Yogyakarta Earthquake and the Alta Mineshaft collapse. He was the Chief of Emergency Management for the US Bureau of Reclamation and managed Department of Interior resources during the California Wildfires of 2007. He deployed to Hurricane Rita with CA-TF5 (Orange County) and the Northridge Earthquake with the Association of General Contractors. He is a Marine Corps veteran who lives by the Chinese term "Gung Ho" meaning a willingness to tackle any task with total commitment.

Hollice Stone, P.E., President of Stone Security Engineering, is a security engineering professional with 17 years engineering, blast, and antiterrorism and emergency response experience. Ms. Stone has been responsible for helping protect people, buildings and campuses from terrorism and has been instrumental in criteria development and educational initiatives in both the engineering and emergency response communities. Ms. Stone has been active in bridging the gap between engineering and emergency response through her work as a 10 year member of California Task Force 3 (ret) and her development and presentation of training programs for first responders including "Firefighter Forcible Entry Through Blast Resistant Windows". Ms Stone is a member of the USACE/FEMA instructor cadre for the Advanced Structures Specialist training course for rescue engineers.

Michael G. Barker, PhD, PE is a Professor at the University of Wyoming after being at the University of Missouri-Columbia for 13 years. He teaches courses in Statics & Elementary Strength of Materials, Dynamics, Structural Dynamics, Design Philosophy, Building Systems and Steel Design. He has conducted experimental and analytical research in the elastic and inelastic behavior of structural systems and has consultant experience in forensic engineering.

Michael was a Structures Specialist for DHS/FEMA's US&R Missouri Task Force 1 before moving to Wyoming. He was also an original member to the FEMA Technical Working Group (now the Structures Sub Group). Michael was deployed to the World Trade Center Response with the Missouri Task Force. He is currently working with the USACE US&R Structures Specialist training program as a lead instructor. He also is an advisor to the Corps' US&R Program in such areas as general program operations, extreme cold weather deployability, and technical rescue training for the military.

At ERDC, **Dr. Stanley Woodson** is primarily responsible for planning and conducting experimental and analytical studies related to the large-deflection response of structures, including the effects of dynamic loads. His work has significantly impacted the Corps' design procedures for both civil works and military structures. For example, Dr. Woodson co-authored the Corps' design manual, Strength Design of Reinforced Concrete Hydraulic Structures, and he co-authored two chapters of the tri-service manual, Design and Analysis of Hardened Structures to Conventional Weapons Effects. He is currently focusing research studies on various aspects of the response of conventional structures to IEDs, and is the ERDC Program Manager of the DHS-sponsored Blast Mitigation of Critical Infrastructure research program. He routinely provides consultation on structural issues throughout the world. He has authored approximately 80 technical publications and presented more than 40 lectures at national/international conferences.

Dr. Woodson assumes leadership roles in professional activities. He is a past chairman of the American Concrete Institute technical committee 370, Effects of Short-Duration Loads, and a current member of committee 421, Design of Slabs. He has served as president of the American Society of Civil Engineers (ASCE) at the local and state levels, and as chairman of the ASCE District 14 Council. Dr. Woodson was selected as the 1992 ASCE Zone II Government Engineer of the Year. He was the 1999 recipient of the Vogel Award, which recognizes outstanding research at the Engineer Research and Development Center. In 2009, Dr. Woodson was award the Meritorious Civilian Service Award, the second highest award provided to civilian employees within agencies of the federal government of the United States.

For the past several years, Dr. Woodson has often taught graduate courses as an adjunct professor at Mississippi State University, through the ERDC Graduate Center in Vicksburg. In particular, his courses are in regard to reinforced concrete structures and blast effects on structures.

Dr. Woodson received his B.S. and M.S. in Civil Engineering (Structures) from Mississippi State University, and his Ph.D. in Civil Engineering (Structures) from the University of Illinois.

Dr. Ted Krauthammer is Goldsby Professor of Civil Engineering at the University of Florida, and Director of the Center for infrastructure Protection and Physical Security (CIPPS). For more than 35 years, his main research and technical activities are directed at structural behavior under severe dynamic loads. Dr. Krauthammer is a Fellow of the American Concrete Institute (ACI), a member of the American Society of Civil Engineers (ASCE), and a member of the American Institute of Steel Construction (AISC). He serves on ten technical committees of ASCE, ACI, and AISC. Dr. Krauthammer is chair of the ASCE/SEI Committee of Blast, Shock, and Impact Effects, and the ASCE Task Committee on Structural Design for Physical Security, and he chaired several other committees at ASCE and ACI. He has written more than 400 research publications, and has been invited to lecture in the USA and abroad. He has been a consultant to industry and governments in the USA and abroad.

Dr. Hyun-Chang Yim is a Research Associate in the Department of Civil and Coastal Engineering at University of Florida. He received his Ph.D. and M.S. degrees at Penn State University. He has been actively involved in research of structural dynamics, highly nonlinear behaviors related to impact, blast, and progressive collapse analysis since 2001. Dr. Yim's research activities have focused on numerical, theoretical, and experimental studies of concrete behaviors under impact and steel connection/frame behaviors under quasi-static, seismic, impact/blast loadings. He is currently leading a project to develop a fast running progressive collapse algorithm, and the behavior of moment resisting connections under severe loading conditions.

Dr. Serdar Astarlioglu is a Research Assistant Professor at the Center for Infrastructure Protection and Physical Security at the University of Florida. He received his Ph.D. degree at Penn State University. Dr. Astarlioglu's background covers structural analysis and design, structural dynamics, engineering mechanics, and numerical methods in engineering. He has been actively involved development of computer software for linear and nonlinear analysis of structures and structural components under static and dynamic loads for over a decade. Dr. Astarlioglu is the lead programmer for the Dynamic Structural Analysis Suite (DSAS) for expedient analysis and assessment of structural components under blast and shock loads

Zee Durón has been a Professor at Harvey Mudd College since 1987, and is currently the Jude and Eileen Laspa Professor of Engineering and Director of the De Pietro Fellowship Program in Civil Engineering at the college. In 2004, Durón was selected by the National Academy of Engineering as one of the nation's brightest young engineers. Durón is considered to be a leading developer of field-test procedures aimed at identifying response characteristics from low-level vibrations that occur naturally in structures. His procedures have been applied to field studies of dams, buildings, bridges, tunnels and rockets. At present, Durón is directing field and numerical model investigations in support of Southern California Edison's risk based performance evaluation of their dams, and currently leads a team of researchers in the development of a monitoring technique designed to alert firefighters of impending collapse in burning buildings. Durón has received funding from a variety of private and government organizations and is a consultant to US and Canadian power utilities, the US Air Force and the US Army Corps of Engineers. Durón has recently been recognized by the US Air Force and the Boeing Company for outstanding contributions leading to the mitigation of shock effects on large launch vehicles, and holds two patents. Durón is a member of ASCE, NFPA and SEM and has published his work in Dam Engineering, HydroReview Magazine, Experimental Technique, the Journal of Structural Dynamics and Earthquake Engineering, and the AIAA Journal. Durón received a B.S. Eng from Harvey Mudd College, a S.M. Civil Eng from MIT, and a PhD in Civil Eng from Caltech.

Dr. Ahmed Al-Ostaz is an Associate Professor of Civil Engineering at the University of Mississippi (Ole Miss). Before joining Ole Miss in 2002, Dr. Al-Ostaz was a Visiting Assistant Professor at Composite Materials and Structures Center and an Adjunct Assistant Professor in the Department of Materials Science and Mechanics at Michigan State University. He focuses his research on utilizing advanced materials (nano enhanced, bio inspired and self-healing materials) in structural applications using multi-scale experimental and numerical tools. He published more than fifty journal and conference papers.

Dr. Al-Ostaz has been the PI and Co-PI on research projects funded by Office of Naval Research, Department of Home Land Security, Air Force Lab (AFL), NASA EPSCoR, Mississippi Space Consortium, Michigan Department of Transportation, Mississippi Department of Transportation, General Motors Company, Research of Excellence Funds (State of Michigan) and NSF-SBIR program with a total funding of more than $5 million. Currently he is a Co-PI in two major research projects sponsored by the Department of Homeland Security Science and Technology Directorate (DHS S&T) through the Southeast Region Research Initiative (SERRI) administered by Oak Ridge National Laboratory and one project funded by Office of Naval Research. He was selected by faculty, students and the engineering alumni of the school of engineering at the University of Mississippi as the Outstanding Engineering Faculty Member of the Year during the academic year 2005-2006.

Alexander H.-D. Cheng, Ph.D. is Dean of Engineering at the University of Mississippi. He obtained his B.S. degree from the National Taiwan University, M.S. from the University of Missouri—Columbia, and Ph.D. from Cornell University, all in Civil Engineering. He was a faculty member at Cornell University, Columbia University, and the University of Delaware, before he joined the University of Mississippi in 2001 as Chair of Civil Engineering Department, and became Dean in 2009.

His research interests include nanomechanics, meshless method, poromechanics, and groundwater flow. He is the Co-Editor of the journal Engineering Analysis with Boundary Elements, and was an associate editor for the Journal of Engineering Mechanics, ASCE. He is also the Editor-in-Chief of the book series Progress in Water Resources, WIT Press. He has authored three books, and edited four specialty books, plus seven conference proceedings. He has published more than one hundred journal papers. He was the co-founder of two conference series: the Biot Conference on Poromechanics, and the International Conference on Saltwater Intrusion and Coastal Aquifers. He was the recipient of the Walter L. Huber Civil Engineering Research Prize from ASCE, and the Basic Research Award from the U.S. National Committee for Rock Mechanics, National Research Council. He currently serves as the Vice President of Engineering Mechanics Institute, American Society of Civil Engineers. He was formerly the Vice President for Academic Affairs of the American Institute of Hydrology. He is also on the Board of Directors of the Wessex Institute of Technology. His recent research projects include two with the Department of Homeland Security, and one with Office of Naval Research, on blast protection of critical infrastructure using nano particle reinforced composites, and on blast and impact protection of navy ships.

Chris L. Mullen, Ph.D. is Associate Professor of Civil Engineering and a newly appointed interim chair of the Department of Civil Engineering at the University of Mississippi. Dr. Mullen received his Ph.D. from Princeton University in 1996 and then joined the faculty at The University of Mississippi. After receiving his MSCE from Rice University in 1981 he spent 5 yr with Mobil R&D, 2 yr with ADAPCO, and 3 yr at Weidlinger Associates. He has taught a variety of courses in the area of Mechanics, Structures, and Design. He has expanded a strong research program in the area of Structural Mechanics and Earthquake Engineering and now serves as Associate Editor of the ASCE/SEI Journal of Structural Engineering in the area of Methods of Analysis. Since 2002, he has served as founding director of the UM Center for Community Earthquake Preparedness and been PI on a number of hazard mitigation planning research projects sponsored by MEMA, FEMA, and others. During Hurricane Katrina he served in MEMA's EOC and as the MS representative for the subsequent FEMA Mitigation Assessment Team. He is now a co-PI on a major blast resistant structures research project sponsored by the Department of Homeland Security Science and Technology Directorate (DHS S&T) through the Southeast Region Research Initiative (SERRI) administered by Oak Ridge National Laboratory. The project has enabled collaboration with two national laboratories: 1) Geotechnical and Structures Laboratory at the US Army Engineering Research and Development Center in Vicksburg, MS, and 2) Building Fire Research Laboratory at the National Institute of Standards and Technology in Gaithersburg, MD.

Dr. Jerome Lynch is an Associate Professor of Civil and Environmental Engineering at the University of Michigan; he is also a faculty member with the Department of Electrical Engineering and Computer Science. Dr. Lynch completed his graduate studies at Stanford University where he received his PhD in Civil and Environmental Engineering in 2002, MS in Civil and Environmental Engineering in 1998, and MS in Electrical Engineering in 2003. Prior to attending Stanford, Dr. Lynch received his BE in Civil and Environmental Engineering from the Cooper Union. His current research interests are in the areas of wireless structural monitoring, feedback control, and damage detection algorithms. Some of Dr. Lynch's more current research has been focused on the design of nano-engineered materials for smart structure applications including carbon nanotube-based thin film wireless sensors for structural health monitoring. Dr. Lynch was recently awarded the 2005 Office of Naval Research Young Investigator Award, 2007 University of Michigan Henry Russel Award, 2008 College of Engineering (University of Michigan) 1938E Award, and 2009 NSF CAREER Award.

Tom Baca, Ph. D. has been deeply involved with the analysis and testing of complex weapon and aerospace structures at Sandia National Laboratories for the past 33 years. He currently manages the Analytical Structural Dynamics Department at Sandia that is responsible for structural dynamics modeling and qualification environment definition for numerous Sandia weapons, wind energy and spacecraft programs. Tom's areas of expertise include structural dynamics analysis, testing and prognostics. Tom has BA and BSME degrees from Union College. He has an MS in Mechanical Engineering and a Ph.D. in Civil Engineering from Stanford University. He is an Associate Fellow of AIAA.

Tom has managed numerous research and development projects including Sandia's early work on structural health monitoring, active structural control using embedded sensors, as well as a current research on embedded MEMS sensors. His group at Sandia has performed embedded sensor experiments on a wide variety of structures including weapon systems, buildings, bridges, wind turbines, and satellite ground stations.

Dr. Feng-Bao Lin is currently an associate professor in the Department of Civil Engineering of The City College of New York and is a leading researcher in the fields of nonlinear numerical analysis, structural dynamics, and nondestructive testing methods. He has conducted various research projects for Argonne National Laboratory, Air Force, NASA, National Science Foundation, and National Institutes of Health. Dr. Lin has been teaching and conducting research in a broad range of areas including nonlinear finite element methods, boundary element methods, structural dynamics, nondestructive testing, constitutive modeling of engineering materials, fracture mechanics, plasticity theory, and damage modeling. Dr. Lin has PE licenses in Taiwan, New York, and Connecticut with many years of consulting experience in the analysis and design of reinforced concrete, prestressed concrete, and steel structures.

Dr. Anil K. Agrawal is a professor of Civil Engineering at the City College of the City University of New York. He received his B.Tech. in Civil Engineering from the Indian Institute of Technology, Kanpur in 1988, M.S. in Earthquake Engineering from the University of Tokyo, Japan, in 1991, Ph.D. degree from the University of California, Irvine, in 1997 and joined the City College of New York in September 1998. Prior to joining the City College of New York, he worked as a post-doctoral researcher at the University of California, Irvine during August 1997 to August 1998. He has published more than 45 Journal papers and more than 100 conference papers. He is currently the member of executive committee of U.S. Panel of International Association of Structural Control and Health Monitoring, Chair of the ASCE Committee on Structural Control, vice-chair of the ASCE Committee on Bridge Inspection, Management and Rehabilitation, Associate Editor of the Journal of Structural Engineering and Associate Editor of the Journal of Bridge Engineering. He was also the chair of the Workshop on Safety and Behavior of Bridges Subjected to Blast in a Multi-hazard Environment, organized in New York City during February 18-19, 2009. His areas of interest include earthquake engineering, structural dynamics, structural control, smart materials and systems, blast load effects of highway bridges, multi-hazard design guidelines for highway bridges, structural health monitoring, bridge management systems and asset management of physical infrastructures.

His recent work in collaboration with Drs. Alampalli and Ettouney on “Theory of Multihazard Design”, published in Journal of Bridge Structures, Vol. 1, No. 3, Sept. 2005, pp. 281 – 291, is a pioneering work on design philosophy for structures when they are likely to be subjected to several types of hazard, including blast loads, during the lifetime of the structure. During last few years, he has carried out an extensive work on blast load simulation of highway bridge components, impact loads on highway bridge components because of truck collisions and seismic fragility of highway bridges in Northeastern USA. The focus of this research has been to develop multi-hazard design guidelines for bridge components subjected to different extreme hazards during its lifetime. He has also developed a deterioration calculated approach based on Weibull-based approach to calculate deterioration rates of aging bridge infrastructures using inspection data for the New York State Department of Transportation. This approach is being used extensively by the NYSDOT to calculate deterioration rates of different bridge components.

Blake Rothfuss, P.E. was graduated from the University of California, Berkeley, 1983 with a Bachelor’s degree in Civil Engineering, and Saint Mary’s College, 2003 with a Master’s degree in Business. Blake is an Associate with Jacobs Associates, where he specializes in tunnels and underground structure design, construction, and rehabilitation. Over his career, Blake has extensive experience in water resources engineering, underwater inspection and construction, and managing heavy construction projects.

Blake has been involved in Urban Search and Rescue (US&R) since 1990, serving as an original member of the FEMA US&R Training Committee and is currently the Lead Structures Specialist for California Task Force 7 (Sacramento). He is a co-instructor for the Corps of Engineers’ Structures Specialist training program, and DHS/FEMA’s Structural Collapse Technician Training. He also teaches Trench Rescue Training. He has participated in many technical rescue missions including the 2005 Hurricane Katrina Search and Rescue, 2004 Walnut Creek (California) Petroleum Pipeline Explosion, 9/11 attack on the World Trade Center, 2001 California State Capitol attack, 1996 Olympic Summer Games (Atlanta), and 1994 Northridge (California) Earthquake. Blake is also a Structures Specialist on the San Francisco Regional US&R Task Force, and a Rescue Engineer with the Moraga-Orinda Fire District.

Thomas C. Clark, P.E. has 20 years of engineering experience including high-rise buildings, post-tensioned concrete, and general commercial and residential design and construction. He has been President of Ironwood Engineering Company and Ironwood Construction Company since 1982, implementing design/build solutions for a wide variety of civil and structural engineering projects and repairs.

Tom is the lead Structures Specialist with CA-TF-4 (Oakland) where he coordinates yearly training sessions for the CA-TF4 engineers. Tom responded to the Northridge Earthquake and World Trade Center Collapse on 9/11/01. He is a member of the DHS/FEMA US&R Structures Sub-group and the California OES (Office of Emergency Services) Heavy Equipment and Rigging Training Working Group. Tom is an instructor for the USACE US&R Training Program, and the DHS/FEMA US&R Structural Collapse Technician course.

John O'Connell has recently retired from the City of New York Fire Department after 26 years of service. For the past 18 years he was assigned to the FDNY's Collapse Rescue Company No.3. John is a principle member of the NFPA 1670 committee program and is the Task Group Chair for the Structural Collapse Section and a former Task Force Leader for New York City's US&R Task Force 1 (NY-TF1). He has been on several DHS/FEMA US&R development committees in the past 17 years, as well as a lead instructor for the DHS/FEMA Rescue Specialist Training. John also serves as a member of the FEMA Incident Support Team (IST) at major disasters, and is currently a Rescue Team Manager for Indiana's US&R Task Force 1 (IN-TF1).

John is an author of numerous articles on structural collapse and technical rescue, and also the book Emergency Rescue Shoring Techniques. He is an Editorial Advisor and Contributing Editor for Fire Engineering magazine. John is also a member of the FDIC's Executive and Advisory boards. He was also a member of the FDNY command staff at the World Trade Center rescue response, John was in charge of all underground search and rescue operations. He operated at the site for 4 months.

John has spent extensive time over the last 17 years in curriculum development for the FDNY, the NY State Office of Fire Prevention and Control, and the FEMA Urban Search & Rescue National Response System. John is the president of Collapse Rescue Systems, Inc., an international training company specializing in technical rescue. John has taught extensively throughout the country as well as Canada, China, Germany, the Middle East and Japan.

Peter B. Keating, Ph.D., P.E. is an Associate Professor in the Civil Engineering Department and an Associate Research Engineer with the Texas Transportation Institute, both at Texas A&M University, College Station, Texas. He received B.S., B.A. (architecture), M.S. and Ph.D. degrees from Lehigh University in Bethlehem, PA. He teaches both graduate and undergraduate courses in structural engineering and performs research primarily in the area of structural fatigue with applications to highway bridges and petroleum pipelines.

Pete has also been a Structures Specialist with Texas Task Force One since 2000. His involvement with US&R began with the 1999 Aggie Bonfire Collapse. He is a member of the FEMA, US&R Structures Sub-group. He frequently teaches the Structural Engineer Systems portion of the Structural Collapse Technician training conducted by TX-TF1's training division. This includes teaching task force members from other states as well as those from Taiwan, the United Kingdom, and the London Fire Brigade.

Vince Chiarito is a research structural engineer in the Structural Engineering Branch, Geosciences and Structures Division, Geotechnical and Structures Laboratory at the Waterways Experiment Station of the U.S. Army Engineer Research and Development Center in Vicksburg, MS.

Mr. Chiarito began his employment at USAERDC (formerly WES) in November, 1980. Since, he has supported structural engineering research for civil and military projects. Project work has included prototype and model vibration studies of several different types of structures and systems and the seismic and blast response of these structures. He has authored or co-authored many technical reports and papers on the structural engineering research efforts and products of the Corps.

Mr. Chiarito received his B.C.E. and M.C.E. in Civil Engineering from the University of Delaware.

Earle Kennett has managed and directed hundreds of projects for federal agencies in architecture and engineering as Vice President at the National Institute of Building Sciences (NIBS) and past Administrator for Research for the American Institute of Architects (AIA). As Vice President atNIBS, he presently manages a number of technical programs including contracts with the Department of Veterans Affairs, NASA, Department of Energy; the Department of Defense, the Naval Facilities Engineering Command, the Army Corps of Engineers, the Air Force, the Department of Homeland Security and the General Services Administration. The International Alliance for Interoperability (IAI), the National CAD Standard, the National BIM Standard, the Building Enclosure Technology and Environmental Council (BETEC), the High Performance Building Council (HPBC), the buildingSMART Alliance, the Facility Maintenance and Operations Committee (FMOC), and the National Clearinghouse for Educational Facilities (NCEF) are under his direction.

He also manages a program concerned with incorporating a large number of design and construction criteria on a website. This system, the Whole Building Design Guide (WBDG) is an innovative concept in information use in the construction industry. The system presently has over 250,000 users and over 2 million documents downloads on a monthly basis, involves over 15 federal agencies and has become the sole portal for the distribution of uniform facility criteria for the military services. Since 2002 he has directed a major security assessment program for the Department of Veterans Affairs that is presently performing security assessments of over 200 VA Medical Centers using a team of over 20 consulting architects, engineers and security experts. As part of this program a methodology was developed and automated which has been published and distributed to the public through the Department of Homeland Security/Federal Emergency Management Agency. He received his Bachelor of Architecture with Highest Honors from the School of Architecture at the University of Tennessee where he received the Chancellor's Citation for Extraordinary Academic Achievement. He also has a Bachelor of Engineering from Memphis State University.

Mr. **Toney Cummins** is a Supervisory Research Civil Engineer and Chief, Concrete and Materials Branch of the Geotechnical and Structures Laboratory (GSL), US Army Engineer Research and Development Center (ERDC). He earned a Bachelor of Science degree in Civil Engineering from the University of Mississippi in 1986. In 1996, Mr. Cummins received a Master of Science degree in Civil Engineering from Mississippi State University. In 1982, He entered civil service as a Student Trainee in the Geomechanics Division, Structures Laboratory, WES. Upon completion of his undergraduate degree, Mr. Cummins was hired as a Civil Engineer in the Geomechanics Division, where he managed and executed laboratory and field experimental programs related to geologic materials characterization and projectile penetration. In 1995, he transferred to what is now the Geosciences and Structures Division, Geotechnical and Structures Laboratory, where his responsibilities were focused on the development of innovative blast and ballistic resistant construction materials and concepts for the construction of new or upgrade of existing structures, development of construction criteria using these materials, and development of analytical methods to evaluate the performance of these materials. Mr. Cummins became the Chief of the Concrete and Materials Branch in 2008, and currently oversees the execution of research and development activities focused on materials development and characterization for both military engineering and civil works applications. Mr. Cummins is the author or co-author of 17 publications in the areas of material characterization, ballistic response, and protective construction, and currently has five patent disclosures under review.

Dr. Bob Welch is a Research Physicist, DB-5 (GS-15 Equivalent). He is a Special Assistant to the ITL Laboratory Director, is Program Manager for the ERDC Carbon Nanotube Technology for Military Engineering Research Program (2006 to present), and is Director of the Shock and Vibration Information Analysis Center (1996 to present). He has a B.S. in Physics from Old Dominion University, and an MS Degree in Engineering Mechanics from Mississippi State University, and a Ph.D. in Engineering Mechanics from Virginia Tech.

His past professional positions include Mechanical Engineer GS-5/7 at Norfolk Naval Shipyard (1974-1975); Research Physicist GS-7/9/11/12/13/14/15 in the Structures Laboratory (1975-1998); and Supervisory Electronics Engineer and Division Chief in ITL, DB-5 (1998-2006).

Bob has about 40 government and other awards. His recent awards include the 2009 ERDC Researcher of the Year Award, the 2009 U.S. Army Corps of Engineers Researcher of the Year Award, a 2009 ERDC Team Award, and a 2009 APEX Award for Publication Excellence.

Bob is a full member of the ASCE, the IEEE, and the American Physical Society, and is the Managing Editor of the Journal of Critical Technologies in Shock and Vibration, and an Associate Editor of the Shock and Vibration journal. He has over 80 publications, 5 U.S. patents, and has directed the past 13 Shock and Vibration Symposia.

Workshop Organizers

Mila Kennett-Reston is a senior program manager in the Infrastructure/Geophysical Division (IGD) of the DHS Science & Technology Directorate. Currently, she manages several projects of the DHS S&T Counter IED Research Program and is responsible for the all IGD International Programs and activities. She is also in charge of a number of workshops to position the vision and goals for the division to support infrastructure resiliency and the infrastructure of the future with underlying principles of national continuity, energy, environmental sustainability, and resiliency. Ms. Kennett-Reston has more than 15 years of experience on projects in the Middle East, Asia, Latin America, Europe, and the United States. Her main focus has been on natural and manmade disaster mitigation; building security; risk assessments; and urban development. She was formerly Deputy Director of the Ministry of Public Works in the Dominican Republic and served as Dean of the School of Architecture and Engineering at the Centro de Estudios Tecnológicos. Ms. Kennett-Reston has been awarded and conducted large research projects for the U.S. National Science Foundation. She was the staff Architect of the Mitigation Branch of FEMA/Department of Homeland Security. She created and managed the Risk Management Series, which are a series of publications devoted to natural and manmade disasters. The Risk Management Series publications are intended to minimize conflicts that may arise from a multihazard design approach and to develop multihazard risk assessments methodologies for buildings exposed to chemical, biological, radiological, and explosive attacks as well as to earthquakes, floods, and high-winds. Ms. Kennett-Reston received a degree in architecture and urban design from the Universidad Autonóma de Santo Domingo and a Master of Arts degree in international development with a major in urban economics from American University in Washington, D.C.

Mohammed M. Ettouney, Ph.D., P.E., F. AEI is a Principal at Weidlinger Associates, Inc. The Inventors Hall of Fame recently awarded Dr. Mohammed Ettouney the inventors award, after being nominated to receive such a great honor by the American Society of Civil Engineers (ASCE). He was also awarded the Homer gage Balcom life achievement award by the MET section of ASCE (2008). He also has just won the Project of the Year Award, Platinum Award (2008) for the "New Haven Coliseum Demolition Project" (ACEC, NY). He is a fellow of Architecture Engineering Institute (AEI). Among other recent achievements are the pioneering work on "Theory of Multi-hazards of Infrastructures", "Theory of Progressive Collapse" (DoD), risk Model for Building Security Council (BSC) rating system and innovative green design method for protecting utilities from demolition / blasting (City of New Haven). He has professional interest in diverse areas of structural engineering as demonstrated through the list of his publications, invited presentations, seminars and sessions organized during national/international conferences and his membership in different professional organizations.

Dr. Ettouney has been with Weidlinger Associates since 1984. He received his Doctor of Science degree in Structural Mechanics from the Massachusetts Institute of Technology (MIT), Cambridge, MA, in 1976. Since then, his interests in the structural engineering profession were both as a practitioner and researcher in multi-hazards safety of structures, probabilistic Modeling of Progressive Collapse of Buildings and uncertainties in structural stability, and blast mitigation of numerous buildings around the world; innovative concepts such as "Probabilistic Boundary Element Method", "Scale Independent Elements", and "Framework for evaluation of Lunar Base Structural Concepts". He is a past president and member of board of governs of AEI, member of Board of Directors of the Building Security Council (BSC), member of numerous technical committees in the fields of building/infrastructures security, earthquake hazards, architectural engineering Non-Destructive Testing and Structural Health Monitoring. He was the chair of AEI National Conference, 2006, and 2008. He has published more than 325 publications and reports, and has contributed to several books.

He introduced numerous new practical and theoretical methods in the fields of earthquake engineering, acoustics, structural health monitoring, progressive collapse, blast engineering, and underwater vibrations. He has co-invented "Seismic-Blast" slotted connection. More recently, he introduced "Economic Theory of Inspection," "General and Special Theories of Instrumentation" and numerous principles and techniques in the field of infrastructures health: they are all pioneering efforts that can help in developing durable infrastructures at reasonable costs. He is co-authoring an upcoming book on "*Infrastructures Health in Civil Engineering,*" CRC Press, 2009. The book is already being described as a breakthrough and original in the field of infrastructures health and preservation.

Eric Letvin PE, Esq, is a Principal Engineer and Attorney for the URS Corporation in Linthicum, Maryland. He has more than 15 years of experience in multi-hazard mitigation and design, serving Federal, State, and local clients. He has experience in infrastructure risk assessments, post-disaster forensic analysis, hazard / threat identification, vulnerability assessments and the design of protective measures for man-made threats and natural hazards. He served as project manager of the FEMA/ASCE team that performed the engineering study of the World Trade Center disaster, and has participated in numerous post-disaster studies including the bombing of the Murrah Building in Oklahoma City, Hurricanes Opal, Ike and Katrina. He has assessed over 200 buildings for risk from terrorist threats and natural disasters.

Mr. Letvin is part of the subject matter expert team working on the development of the rapid visual screening tool with FEMA, DHS' Science &Technology Directorate. He is the program manager for URS's contract with DHS' Protection and Programs Directorate (Office of Infrastructure Protection). He regularly teaches courses in building design in disaster-resistant construction for FEMA throughout hurricane-prone regions of the US. He has taught FEMA's Building Design for Homeland Security Course 23 times to over 400 people in the past 5 years which teaches students how to conduct risk assessments of critical infrastructure and design protective measures.

Mr. Letvin has been the consultant project manager for numerous FEMA mitigation publications including the recently released FEMA 453, Design Guidance for Shelters to Protect Against Terrorist Attacks; FEMA 426, Reference Manual to Mitigate Potential Terrorist Attacks Against Buildings; FEMA 452, Risk Assessment: A How-To Guide to Mitigate Potential Terrorist Attacks and FEMA 428, Primer to Design Safe School Projects Against Terrorist Attacks.

Mr. Letvin holds a bachelor's and master's degree in civil engineering from Syracuse University and received his Juris Doctor from the University of Maryland.

WORKSHOP AGENDA

Stabilization of Buildings Workshop
Sponsored by
DHS S&T Directorate and the U.S. Army Engineer Research and Development Center
August 25-27, 2009

Agenda

Day 1 – Tuesday, August 25, 2009

Theme: The first day of the workshop concentrates on the problems of building stabilization. This includes, but is not limited to the definition of building instability conditions, current assessment methodologies (both off- and on-site) for the identification of buildings and building systems that are near failure or collapse, and the limitations of current assessment methods. Real-time decision-making techniques, case studies and experiences from different panelists, and presenters will round up the discussions on problems and roles.

7:30 - 8:00 Registration

8:00 - 8:30 Welcome and Introductions
Mary Ellen Hynes, David Pittman, Stephen Hancock

8:30 – 10:45 ***Session 1*** Overviews

8:30 – 9:15 Keynote: *Blaine Brownell*
Arts and Sciences of Buildings Stabilization

9:15 – 9:45 *Amar Chaker*
Efforts of ASCE Regarding Building Stabilization after Abnormal Events

9:45 – 10:15 *Paul Mlakar*
Experiences from 9-11: The Stabilization of the Pentagon Building

10:15 – 10:45 *Stephen Cauffman*
NIST Overview and Efforts on Stabilization of Buildings after Terrorist Attacks

10:45 – 11:00 Break

11:00 – 1:00 ***Session 2*** First Responders

11:00 – 11:30 *Philip Parr*
Real Time General Assessment Issues and 9/11 Experiences: Fire Fighters View Points

11:30 – 12:00 *David Hammond*
Rescue Engineering: Practical Aspects of Building Stabilization in a Search & Rescue Environment

12:00 – 12:30 *Holly Stone*
The Collapsed Structure Disaster Work Environment

12:30 – 1:00 *Michael Barker*
Hazard Assessment & Mitigation Techniques for Explosion Collapsed Buildings

1:00 – 2:00 Lunch

2:00 – 4:00 ***Session 3*** Structural Engineering Concepts

2:00 – 2:15 *Mohammed Ettouney*
Why Buildings Become Unstable? The Basics

2:15 – 2:30 *Eric Letvin*
Concepts of Advanced Engineering – Roles of Ultra-Performance Structures: a New Way of Thinking after 9/11

2:30 – 3:00 *Najib Abboud*
Fire and Building Stabilization: Overview, Case Studies and Recommendations

3:00 – 3:30 *Stanley Woodson*
Can Strengthening for Earthquake Improve Blast and Progressive Collapse Resistance?

3:30 – 4:00 *Lee Glascoe*
Analytical Techniques: View from National Labs

4:00 – 4:15 Break

4:15 – 5:15 Breakout Sessions
- 1A Current practices: shortcomings and strengths
- 1B Stakeholders: roles, responsibilities, and interactions
- 1C Structural engineering: state of the art and technology transfer

5:15 – 5:30 Break, Buses back to hotels

5:30 – 6:00 Moderators and co-moderators meet to prepare for reporting to general assembly next morning

6:30 – 8:30 No Host Dinner – Bus pickup from Marriot Hotel at 6:30PM

Day 2 – Wednesday, August 26, 2009

Theme: The second day of the workshop will concentrate on discussing the solutions that would help in identifying unstable buildings and how to shore them up. This includes efficient, economic, and proven techniques that might be in use now for building (or other infrastructures) stabilization. Of interest are innovations in technology, such as portable structures or inflatable barriers that can be deployed under emergency conditions to allow first responders to access areas of high risk, and advanced materials that might be used in such conditions to stabilize building components. Also of interest are advanced monitoring methodologies and technologies (both off- and on-site) for the identification of buildings that are near failure or collapse. Experiences from other communities (such as aero, offshore platforms, or mechanical fields) might also be discussed.

8:30 – 9:00 Reporting of Day 1 sessions and resolutions
Introductions to Day 2

9:00 – 10:30 ***Session 4*** Analytical Monitoring and Assessment of Near Collapse Buildings

9:00 – 9:30 *Ted Krauthammer*
Expedient Blast Damage and Building Stabilization Assessment

9:30 – 10:00 *Zee Duron*
Monitoring Stability Loss in Burning Buildings

10:00 – 10:30 *Ahmed Al-Ostaz*
Structures Subjected to Blast Loading: Protection, Stabilization and Repair

10:30 – 10:45 Break

10:45 – 12:15 ***Session 5*** Experimental Strategies for Examining Near Collapse Buildings

10:45 – 11:15 *Jerome Lynch*
Monitoring Strategies for Rapid Assessment of Structural Condition and Stability Following a Terrorist Event

11:15 – 11:45 *Thomas Baca*
Structural Health Monitoring: Overview and Challenges Ahead

11:45 – 12:15 *Feng-Bao Lin*
Structural Integrity Monitoring System for Detecting Imminent Collapse of Buildings

12:15 – 1:30 Lunch

1:30 – 3:00 ***Session 6*** State of the Art Equipment, Techniques and Strategies Needed for Near Collapse Buildings

1:30 – 2:00 *Blake Rothfuss*
Shoring Stabilization of Buildings in an Urban Search & Rescue

2:00 – 2:30 *Peter Keating*
Techniques and Equipment for Monitoring Damaged Structures

2:30 – 3:00 *Vince Chiarito*
State-Of-The-Art Remote Monitoring of Buildings

3:00 – 3:15 Break

3:15 – 4:45 Breakout Sessions
2A Analytical monitoring and assessment of near collapse buildings
2B Experimental strategies for examining near collapse buildings
2C Decision making: onsite and offsite

4:45 – 5:00 Break, Buses back to hotels

5:00 – 5:30 Moderators and co-moderators meet to prepare for reporting to general assembly next morning

Day 3 – Thursday, August 27, 2009

Theme: The final day of the workshop explores the *future*. *This includes 1) innovative solutions, 2) improving interactions and relationships and cost-effective opportunities for DHS and other governmental agencies (local, state, and federal), international entities, the private sector, and academia, and 3) the role of technology (online assessments, education, etc.), knowledge gaps, technology transfer and research needs.*

8:30 – 9:00 Reporting of Day 2 sessions and resolutions
Introductions to Day 3

9:00 – 10:00 ***Session 7*** The Future

9:00 – 9:20 *Earle Kennett*
High Performance and Integrated Design Efforts for Improving Building Stabilization

9:20 – 9:40 *Toney Cummins*
Rapidly Emplaced Composite Structural Support Systems

9:40 – 10:00 *Charles Welch*
Inverse Triaxial Structural Element – Implications for Rapid Building Stabilization

10:00 – 10:15 Break

10:15 – 11:15 Breakout Sessions
- 3A High performance building design
- 3B Innovative systems and equipments
- 3C Advanced materials

11:15 – 11:30 Moderators and co-moderators meet to prepare for reporting to general assembly

11:30 – 12:15 ***General Assembly***
General Recap of the workshop
Closing remarks by DHS S&T
Mary Ellen Hynes, Stan Woodson, Stephen Hancock

12:15 **Adjourn,** Buses depart for Jackson Airport and Hotels

Stabilization of Buildings Workshop Attendees

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First Draft Research Agenda
Stabilization of Buildings

- Formation of Task Committee for the Stabilization of Buildings
- Structural Evaluation
- Criteria for Interpretation, Dissemination of Data, and Triage and Decision-making Methods
- First Responders, Search and Rescue Issues
- Understanding Innovative Concepts, Materials, and Deployable Technology Systems
- Testing Innovative Materials and Deployable Technology Systems
- Outreach Efforts

I. Formation of Task Committee for the Stabilization of Buildings

II. Structural Evaluation (Task Committee Assignments)

1. Definition of Parameters and Sensing
2. Automated Documentation of Monitoring Results
3. Leveraging existing technologies available in military or intelligence community
    - Fire
    - Gas
    - Structure
        - Envelope
        - Beams
        - Columns
        - Connections
        - Progressive Collapse
        - Electrical, pipelines
    - Nonstructural
    - Underground Structures

4. Rapid Risk Assessment and Definition of Parameters (Task Committee Assignments)
    - Identify available methods and technologies
    - Rely on rapid visual screenings and imaging tools (i.e., laser scanners, sonar technologies, GPS)
    - Expand the understanding of structures already damaged by explosives (coordinate with Weidlinger-Urban Canyon project)

- Site and Utilities
- Architectural
- Structural
- Building Envelope
- Mechanical, electrical, plumbing
- Underground structures

III. Criteria for Interpretation, Dissemination of Data, and Triage and Decision-making Methods (workshop)

IV. First Responders, Search and Rescue Issues (workshop)

- Identify sensor technology that allows effective monitoring
- Identify user-friendly technology that won't hinder the mission and safety of first responders
- Facilitate interpretation of data for an imminent collapse of buildings
- Facilitate reconciliation of field data with analytical models
- Identify research and training needs for fire-structure interaction and blast-related damage
- Facilitate reach-back or remote support (tele-engineering)

V. Understanding Innovative Concepts, Materials, and Deployable Technology Systems

1. Involvement and interaction with
    - Universities
    - Labs
    - Researchers
    - Federal Agencies
    - Associations
    - Industry
    - International Partners
    - Building Owners
    - First Responders
    - Building Designers
2. Organization of a Clearing House (identification, testing protocols, dissemination, confidentiality issues)
    - Coordinate with advanced materials database prepared by NIBS
3. High Performance Buildings, Continuity of Operations, and Life Cycle

VI. Testing Innovative Materials and Deployable Technology Systems

Leveraging existing DOD, Military technologies in a controlled environment

VII. Outreach Efforts

Market Demand – Public Relations

Papers Submitted to the 2009 Stabilization of Buildings Workshop

Rescue Engineering: Practical Aspects of Building Stabilization in a Search & Rescue Environment

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ABSTRACT

Collapse rescue operations are dangerous, rapidly evolving efforts focused on finding and extracting trapped and entombed victims, while avoiding harm to the rescuers and further harm to the victims. Stabilization of damaged structures is an integral part of building collapse rescue operations. The Department of Homeland Security Federal Emergency Management Agency (DHS/FEMA) and the U.S. Army Corps of Engineers (USACE) Urban Search & Rescue programs have developed a state of practice for conducting search and rescue operations in fully or partially collapsed buildings. Over the past 15 years, structural engineers in these programs (Structures Specialists) have been rigorously trained and have gained valuable experience in building collapse incidents and building stabilization. The building stabilization state of practice has evolved as these professionals have gained this experience at these disasters, conducted full-scale testing of stabilization methods, and developed tools and techniques to monitor the stability of damaged structures. This paper presents a brief overview of the DHS/FEMA and USACE Urban Search & Rescue programs; the roles, responsibilities, and training of rescue engineers within the program; experience-based building stabilization principles in a rescue environment; current testing and tool development; and thoughts on potentially productive areas of future research and development.

INTRODUCTION

This is the engineering challenge we face: It's the evening of April 19, 1995, and a team of 60 urban search and rescue responders with 60,000 pounds of specialized equipment arrive in Oklahoma City ready to go to work in the building—or what is left of it (Figure 1) after the explosion—to find and extract entombed victims. The command structure of the team, working with the Oklahoma City Fire Department, are making operational plans and want the rescuers deployed for operations within the hour. They need immediate input on the overall stability of the building, structural hazards rescuers face, and possible mitigation measures to reduce operational risk. The two engineers on the team are expected to offer critical advice with limited information and limited time as they are confronted with a rapidly changing situation with great pressure for immediate action. What can an engineer do in this environment?

Figure 1: Oklahoma City Bombing

BACKGROUND

Collapse rescue operations are dangerous, rapidly evolving situations focused on finding and rescuing trapped and entombed victims, while avoiding harm to the rescuers and further harm to the victims. Victim rescue must be balanced with risk to rescue personnel. Since the potential for live victim recovery decreases rapidly with time, acceptance of risk is generally greater earlier in a rescue operation than later in the operation.

Building damage requiring rescue operations can occur in many shapes and from a wide variety of initiating incidents, such as: wall or parapet failures caused by deteriorating building materials, soft story collapses due to earthquakes, collapse of all or portions of buildings due to latent defects, or collapse of major portions of buildings due to explosive attack. Regardless of the cause of the collapse, rescue operations will ensue if people are believed to be trapped in the rubble or damaged structure.

Stabilization of damaged structures is an integral part of building collapse rescue operations. Firefighters and first responders have been dealing with these situations for years, developing stabilization techniques through trial and error based on experience and readily available material and equipment.

URBAN SEARCH & RESCUE PROGRAM

The Department of Homeland Security Federal Emergency Management Agency (DHS/FEMA) and the U.S. Army Corps of Engineers (USACE) turned their attention to major structural collapse response in the late 1980’s and early 1990’s, developing the Urban Search & Rescue (US&R) program, with USACE developing the Structures Specialist Training courses. The DHS/FEMA US&R program is part of Emergency Support Function (ESF) 9 of the National Response Framework and consists of 28 collapse rescue Task Forces and three Incident Support Teams (IST) located across the United States. The teams are highly trained urban search and rescue responders outfitted with equipment and materials required for extended operations in major structural collapses. Depending on the type of response, the teams are deployed as 34-, 60-, or 80-person task forces. When deployed in the 60- or 80-person configurations, each team includes two engineers trained in search and rescue operations and building collapse engineering. They are known within the response system as Structures Specialists.

At the same time the DHS/FEMA program was being developed, USACE developed a complementary cadre of Structures Specialists to work in conjunction with the DHS/FEMA US&R program to supplement the demanding technical needs for search and rescue operations in damaged structures.

Since 1992, the DHS/FEMA/USACE US&R teams have been deployed to more than 30 incidents, including two earthquakes, three terrorist attacks, a building gas explosion, a grain elevator explosion, multiple hurricanes, one typhoon, and pre-deployments for five National Special Security Events.

Two of the teams are also international assets, deployed through the U.S. Agency for International Development. These teams have been deployed to the 1998 embassy bombings in Kenya and Tanzania, earthquakes in Turkey, Taiwan, and Iran, and to the recent school building collapse in Haiti. In addition to the DHS/FEMA and USACE programs, there are numerous state and regionally sponsored urban search and rescue teams.

STRUCTURES SPECIALISTS

Structures Specialists perform various structural related tasks for a US&R Task Force or an IST during incident operations. A Structures Specialist's duties may include:

- Assessing the immediate structural condition of the affected area of Task Force operations, which includes identifying structure types, specific damage, and structural hazards.
- Identifying and prioritizing search operations based on building use, type of probable voids, and time to rescue.
- Recommending the appropriate type and amount of structural hazard mitigation in order to manage risks to task force personnel.
- Monitoring damaged structures while rescue and recovery operations are proceeding.
- Assuming an active role in implementing approved structural hazard mitigation measures as a designer, inspector, and possibly a supervisor.
- Coordinating and communicating critical assessment, mitigation and monitoring operations to those in need of the information.

There are approximately 300 trained Structures Specialists in the United States. Before these Structures Specialists can successfully support search and rescue operations, they must understand not only traditional engineering concepts, but also rescue objectives and philosophies, available tools and equipment, skills and abilities of rescuers, scene safety, and where they, as engineers, fit into the system.

The minimum DHS/FEMA approved training therefore includes:

- Rescue Systems I – 40 hr course on rescue operations, tools and equipment, and rescue capabilities.
- Structures Specialist I – 45 hr course on building collapse, rescue engineering concepts, and current state of practice using past incident experiences.
- Structures Specialist II – 50 hr course providing advanced training and re-certification training.
- Topical courses on weapons of mass destruction, hazardous material training, heavy rigging, etc.

This training facilitates the Structures Specialist becoming a trusted, contributing member of an urban search and rescue team. However, engineers must also be understood by search and rescue responders who will implement engineering recommendations. Therefore, training classes have also been developed and presented by Structures Specialists for the search and rescue responders.

BUILDING STABILIZATION CONSIDERATIONS IN A RESCUE ENVIRONMENT

The three characteristics of a full or partial building collapse that must be assessed by the Structures Specialist are:

- Viable void potential
- Structural hazards
- Hazard mitigation strategies

Viable Voids

The primary focus for search and rescue teams is rescuing live victims. This means finding and accessing voids in which live victims are entombed, here called viable voids. In assessing the potential for viable voids, there are two aspects (beyond the initial evaluation of the probability of occupants in the building prior to the event) that must be considered: the physical potential for voids and the viability of any victims in those voids.

Void potential is a function of total energy released (during the initial event and any secondary events), structural type and configuration, the collapse pattern, building contents, and other factors.

In addition to the physical presence of voids, the viability of potential victims in those voids must also be considered. A physical void that initially protects a victim from crushing may become non-viable due to various secondary events such as fire, smoke, temperature extremes, aftershocks, flooding, chemical exposure, and time.

Structural Hazards

While the first inclination of an engineer may be to assume that progressive collapse of the remaining structure is of the greatest concern, experience has shown that this is not usually the case. While secondary collapse cannot be ignored (story mechanism, overturning, etc.), other structural hazards are often a more immediate concern. The predominant hazards of immediate concern are:

- Falling of loose debris (the cause of the only fatality of a responder in Oklahoma City).
- Shifting debris pile.
- Shifting/sliding/dropping of elevated failed components.
- Local shear/flexural failure of beams/slabs.
- Local crushing/buckling of walls/columns.

The significance of these hazards often changes over the course of rescue operations and must be re-evaluated on a continuing basis. The changing conditions may include external events such as aftershocks, secondary detonations, and weather; or they may be operations related changes such as debris removal, vibrations from operations and load changes due to rescue personnel and equipment.

Mitigation Measures

Once potential viable voids and structural hazards have been identified, mitigation measures can be planned and implemented to manage the risk during operations. There are no pre-set, cookie-cutter solutions to hazard mitigation; rather the rescue team, including the Structures Specialist, must assess the situation and apply a combination of the five basic mitigation strategies based on the premise of risk versus reward:

- Avoidance
- Exposure Time Reduction
- Removal
- Stabilization
- Monitoring

If victim location and building stability allow, the most efficient and effective methods of hazards mitigation are avoidance and removal. If an area of particular hazard can be avoided without negatively impacting rescue operations, then that area can be designated a no-enter zone. If a particular hazard can be removed in a relatively short amount of time without further destabilizing the damaged structure, then the hazard should be removed.

Another efficient method of hazard risk reduction is to limit the time of exposure, and to limit the number rescuers being exposed to a potentially dangerous situation. Risk is a function of both severity and exposure.

However, in major collapse events, avoidance or removal will most likely be applicable in a minimum number of instances. The primary mitigation method is to stabilize the structural system an adequate amount to allow rescuers access to potential victim locations at a reduced risk. There is a large array of stabilization techniques in a rescue team’s toolbox. Some of these include vertical and lateral shores, tie-backs, window and door shores, and pneumatic shores and airbags.

Stabilization techniques must match the rescue environment. They must be:

- Easily understandable by rescue personnel.
- Quickly fabricated and erected.
- Able to be placed in small, unstable situations with limited visibility and access.
- Made from materials that are strong, light, portable, and adjustable.
- Able to reliably support the structure as gently as possible.
- Designed and implemented to have ductile, predictable failure modes.

In some instances, none of the above mitigation measures are able to satisfactorily remove hazards or reduce risk. In these cases, the hazard, whether it is a partially collapsed portion of the structure or an overhead hanging slab, should be monitored so that additional movement can be identified and evacuation procedures initiated if needed. It is important to note that only certain modes of failure lend themselves to effective monitoring. Monitoring of a damaged structure is only effective if the monitoring can identify precursors of foreseeable failure modes with sufficient lead time to sound the alarm and evacuate the area. Thus, monitoring is only effective for ductile modes of failure where the structure (or some component) undergoes significant, gradual displacement prior to collapse. Racking of a soft story in a wood frame building is an excellent candidate for monitoring, as are flexural failures and lateral sway of ductile elements. Dislodged masonry veneer that could fall suddenly is not a good candidate for monitoring. Monitoring can also be effective for evaluating changing conditions, such as the effects from removal of stabilizing debris, the effects of aftershocks, or movement of a retaining wall or landslide mass.

CURRENT TESTING AND TOOL DEVELOPMENT

As the US&R program has progressed, basic research, testing and development has been performed by several interested groups to quantify strength of existing stabilization techniques, refine existing practices, examine observed behaviors, design and build engineering tools, and solve identified problems. The research, testing, and development have been guided by successful practice and identified practical concerns based on experiences and challenges at real-world incidents. Some of the testing and experimentation that has been performed include:

- Capacity and failure modes of vertical shoring systems due to vertical loading and combined vertical and lateral loading (NASA Ames Moffet Field in Mountain View, California and Texas A&M University).
- Capacity of Lateral (raker) shores (CA-Task Force 3 Rescue Site in Menlo Park, California).
- Effects of micro-cracking on damaged concrete structural elements (Texas A&M University).
- Methods for safely cutting P-T tendons (VA-Task Force 1 rescue site in Fairfax, Virginia).
- Capacity of proprietary shoring and bracing systems manufactured by several vendors (vendors, CA-TF3 Rescue Site, NASA Ames Moffet Field).

Engineering tool refinement and development includes:

- Wireless Building Monitoring System (WBMS).
- Surveying Total Station (development of monitoring methodology geared to rescue environments).

The WBMS was developed in the aftermath of Oklahoma City to provide a means to safely and continuously monitor a damaged structure for movement without dedicating an individual to the task. The system is comprised of bi-axial, gravity referenced rotational transducers that can be attached to the structure and communicate wirelessly with a receiver and display unit monitored by an engineer up to 1,000 feet away. The system provides a time history of building movement (or lack thereof) and triggers can be set to provide an audible alert if movements exceed pre-determined levels. Thus, a single engineer, equipped with a personal digital assistant (PDA) and an earphone, can monitor movement at up to four locations within a damaged structure while carrying on other duties.

Similarly, a Total Station can be used to monitor several locations on buildings with minimal effort. Protocols have been developed and included in the Structures Specialist training for using the Total Station in a building collapse incident.

FUTURE RESEARCH

Major building collapses are somewhat like war-time conflicts: each requires a unique strategy and each requires a different set of tools/weapons. When implementing changes to the search and rescue system, these changes are generally based on the experiences of the last incident, just like in times of war. From the rescue engineering perspective, the following have been learned from past incidents.

Each incident has posed dramatically varied structural challenges, the most significant of which is assessing the short-term strength and stability of damaged structures and structural components. Time and information are both in short supply, so assessment methods must be simple, clear, and qualitative. Mitigation methods will generally be implemented by rescue team members (firefighters) or local contractors, so the measures must be simple, adaptable, and easily implemented in a rescue environment. Monitoring tools must likewise be adaptable AND appropriate monitoring decision-making criteria must be developed (i.e., to distinguish between benign diurnal structural movement due to solar heating and critical cyclic ratcheting toward failure).

Although not an exhaustive list, the following are four of the authors' thoughts on potentially productive areas of future research and development.

1. <u>Research on the remaining strength, ductility, and failure modes of damaged/ compromised structural elements.</u> There is an existing knowledge base of component behavior for both maximum strength and post maximum strength behavior in terms of design behavior requirements. However, assimilating this data and developing means for its use in search and rescue is needed to improve the Structures Specialist's tasks of assessment, mitigation, monitoring, and search and rescue operations.
2. <u>Better quantification of the risk versus reward assessment process</u>. If the probability is high that there is a live victim in a damaged structure, then the acceptable risk in rescuing

that victim is also high. If the incident has progressed for a long time, or if the authorities have moved from rescue mode to recovery mode, then the acceptable risk is low, and more effort and time would be justified for heavy mitigation efforts. However, these decisions have been very subjective in the past based on anecdotal experience. On the risk side of the equation, the question is what is the likelihood of a damaged building collapsing in the next hour? The next day? Next week? On the reward side, the question is what are the potential rewards if a victim is extracted one hour earlier? Or one day earlier? A more definitive process is needed for effective management of risk.

3. Additional research on mitigation shoring systems. The current knowledge base for shoring capacity and ductility is somewhat sparse. Shoring is the primary mitigation method for building stabilization and, thus, the primary method for managing risk to search and rescue personnel. There is much research that should be done to better quantify shoring system capabilities and usefulness. In addition, there are still basic shoring design philosophies that also need attention such as whether shoring should be there to only take additional possible loads or whether the shoring should replace the existing load resisting system.

4. Expand on the WBMS system concept to develop additional monitoring devices and working platform. Additional real-time structural response data, such as vibration/acceleration, acoustic emission, strain, and displacement, would allow a greater range of structural behavior to be monitored. The first aspect of this work would be to identify the best indicators of impending movement or failure. The second aspect would be to identify the appropriate transducers and prove the concept. A rigorous and reliable working platform for the monitoring system would be crucial for efficient implementation by the Structures Specialist.

SUMMARY

As DHS embarks on this effort to develop building stabilization methods and procedures, and identifies a research agenda to meet this goal, it is important to examine past practice: its history, its successes, and its capabilities for building stabilization. The DHS/FEMA and USACE Urban Search & Rescue programs have developed a state of practice for conducting search and rescue operations in fully or partially collapsed buildings. Engineers in these programs (Structures Specialists) have been rigorously trained and gained invaluable experience at actual building collapse incidents in building stabilization for over 15 years. The building stabilization state of practice has evolved as these professionals have gained this experience at these disasters. This paper presents only a flavor of the history, the success, and the capabilities of the DHS/FEMA and USACE Structures Specialist system for building stabilization.

The Collapsed Structure Disaster Work Environment

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ABSTRACT

For over three decades the United States has been developing assets to respond to natural and man-made disasters. When the disaster involves collapsed buildings, the Urban Search & Rescue component within the National Response Framework comprises DHS/FEMA US&R Task Forces located across the country that can respond within hours. The multi-disciplinary Task Forces have advanced search capabilities to locate, and heavy rescue capabilities to extricate, trapped victims. The Rescue Trained Professional Engineer (Structures Specialist) plays a key role in assessing the damaged structure and mitigating risks to the search and rescue personnel. This paper presents a history of the US&R response system and the current operational capabilities of the DHS/FEMA Urban Search & Rescue program.

INTRODUCTION

The United States has a National Response Framework to respond to natural and man-made disaster incidents. When the disaster involves the collapse of buildings, the National Response Framework includes an Urban Search & Rescue (US&R) component that works within an Incident Command System to locate and rescue trapped victims. A critical element in the US&R system is the Rescue Trained Professional Engineer (Structures Specialist) that has been trained to assess the hazards of a collapsed building environment and recommend mitigation techniques to reduce the risk to personnel during the search and rescue operations. The US&R system has evolved over three decades to become a robust and effective response asset. This paper presents the history of the DHS/FEMA Urban Search & Rescue program, the DHS/FEMA US&R Task Force, disaster site management and planning activities, and a description of an US&R response to a collapsed building incident.

NATIONAL URBAN SEARCH & RESCUE RESPONSE SYSTEM

The Beginnings

The devastating 1985 Mexico City earthquake, followed by earthquakes in San Salvador (1986) and Armenia (1988), clearly demonstrated that successful search and rescue in an urban environment required the use of highly trained and specially equipped personnel.

Rescue teams from many countries, including the U.S., responded to these disasters. The teams were confronted with collapsed or partially collapsed heavy concrete structures that entombed numerous live victims. Successful rescue depended on timely removal of the victims as well as their proper medical treatment. The thoughtful coordination of the search, rescue, medical, and technical (engineering, heavy rigging, and hazardous materials) aspects of urban search and rescue was crucial, but very difficult to accomplish in the chaotic disaster environment.

For the most part, independent groups of search specialists (mostly canine), heavy rescue fire fighting rescue specialists, medical responders, and a very few engineers constituted the response to these earthquakes. Their efforts were hampered by lack of coordination and unfamiliarity with each other's location, needs, and capabilities. In a few cases, coordination between technical efforts and canine search, followed by rapid deployment of heavy rescue groups, led to dramatic positive removal of entombed victims. During the two weeks following the Mexico City earthquake, approximately 150 entombed live victims were removed, however, about the same number of rescuers perished during rescue operations.

During 1986, within the US a number of public and private search and rescue organizations began to focus on the concept of creating well trained and well equipped, multi disciplined organizations to respond to heavy rescue in an urban environment (Urban Search & Rescue). The dialog was initially between the historically established canine search groups and heavy rescue firefighter entities, but was augmented by volunteer doctors who had experienced confined space medical problems in coal mine cave-ins. The few structural engineers familiar with past practice and the need for an organized approach also became part of this movement.

Developing a National Response Plan

The Robert T. Stanford Disaster Relief and Emergency Assistance Act of 1988 substantially increased the role of the Federal Government in disaster response. The Act revised and amended the Disaster Relief Act of 1974 to expand the scope of disaster relief programs and defined the role of the government in all four phases of the disaster management cycle: Preparation, Response, Recovery, and Mitigation. With the broadening of the federal role in disaster response, it soon became apparent that there was a need to coordinate the efforts of the various federal agencies that had the capabilities to respond to disasters. The Federal Emergency Management Agency (FEMA) began a multi-agency planning effort which led to the publishing of the Federal Plan for Response to a Catastrophic Earthquake in 1987.

This Response Plan represented an agreement among the various federal agencies with disaster response capabilities as to the role each would play in a catastrophic earthquake. The Response Plan was oriented primarily towards a major earthquake in California and represented an "all or nothing" approach; the entire plan would be implemented if considered necessary. The Response Plan was first implemented in 1989. Hurricane Hugo in Florida and the Loma Prieta earthquake in California, both in 1989, demonstrated the value of the pre- planning, but also pointed out several problems with the Response Plan effectiveness. In each case, the catastrophic event envisaged by the plan did not actually occur, yet the capabilities of local governments were severely over-taxed. Some federal assistance was needed, but the necessity for a massive federal response did not materialize. Federal agencies were unsure how to react to a less than full activation. It was also obvious that the Response Plan would need to consider a range of severity of events, even those that are less than catastrophic. This need for a multi-hazard, flexible Response Plan was further confirmed during Operation Desert Storm, since plans that had been developed for a full mobilization had to be down-sized.

From the lessons of the Loma Prieta earthquake and Hurricane Hugo, FEMA coordinated a new planning effort that resulted in the Federal Response Plan (now called the National Response Framework, or NRF). This plan represented a coordinated approach to providing response for a variety of disasters. Its hallmark is flexibility, allowing federal officials to activate portions of the plan appropriate to the level of response required. Under the plan, federal activities are coordinated by an Emergency Response Team (ERT) headed by a presidential-appointed Federal Coordinating Officer (FCO). All Federal emergency capabilities and assets are now grouped by function rather than by agency, allowing for a fast coordinated response to requests for assistance. A functional unit is called an Emergency Support Function (ESF) and is headed by a lead agency charged with coordinating the activities of that function. FEMA was assigned the Urban Search & Rescue Emergency Support Function (ESF 9).

DHS/FEMA Urban Search & Rescue System

In June of 1989, FEMA's Office of Emergency Management and the US Fire Administration met to review the lessons learned from past incidents and to consider the possibility of a national Urban Search & Rescue initiative. Several problems became evident:

- Traditional search and rescue was largely confined to rural environments with only a limited number of search dogs having been trained for the urban environment;
- Local fire departments, who are usually charged with urban search & rescue in most jurisdictions, were not equipped for heavy rescue (lacking specialized tools and training) and would be overwhelmed by the requirements of a catastrophic event; and
- There were no nationally accepted standards for personnel, training, or equipping of Urban Search & Rescue teams.

Hurricane Hugo and the Loma Prieta earthquake confirmed these concerns and added the problem that there was extreme danger from structural collapses and that structural collapses will immediately overwhelm local resources. During the response to these events, it became evident that the federal government had no way to identify and mobilize any existing assets to respond to such an incident. Well trained and equipped medium and heavy urban search and rescue teams did not exist in the United States. It was clear that a new and extensive approach was required to meet urban search & rescue needs.

In January of 1990, FEMA convened an Urban Search & Rescue (US&R) workshop in Seattle. Eighty-five invited participants represented all geographic regions of the United States and all relevant technical disciplines. The group evaluated the status of current national US&R capabilities and identified requirements for a national Urban Search & Rescue system (structure, equipment, and training). The workshop also suggested methods for developing such a system. The workshop results recommended that locally based, multi-disciplined groups (FEMA US&R Task Forces) be developed, equipped and trained to respond to national incidents. Further definition and refinements occurred when a select group of experts (FEMA US&R Advisory Committee) met with FEMA officials in April 1990. The Advisory Committee selected top experts to chair various Working Groups in order to develop guidelines for Standards, Equipment, Management and Coordination, Communication, and Training. The work and recommendations from these Working Groups became the base documents that defined the FEMA US&R Program.

In May of 1991, FEMA invited states and local jurisdictions to apply for grants to become sponsoring agencies for a US&R Task Force. In August of that year, a Technical Review Panel screened the 34 applications received, and on the basis of the panel's recommendations, FEMA selected 25 jurisdictions as sponsoring agencies. Since the initial 25 were selected, the number of

FEMA US&R Task Forces has grown to 28. Figure 1 shows the location of the 28 FEMA Task Forces.

In 2002, FEMA and the Urban Search & Rescue part of FEMA were placed within the Department of Homeland Security (DHS) and now the US&R Task Forces are called DHS/FEMA Task Forces.

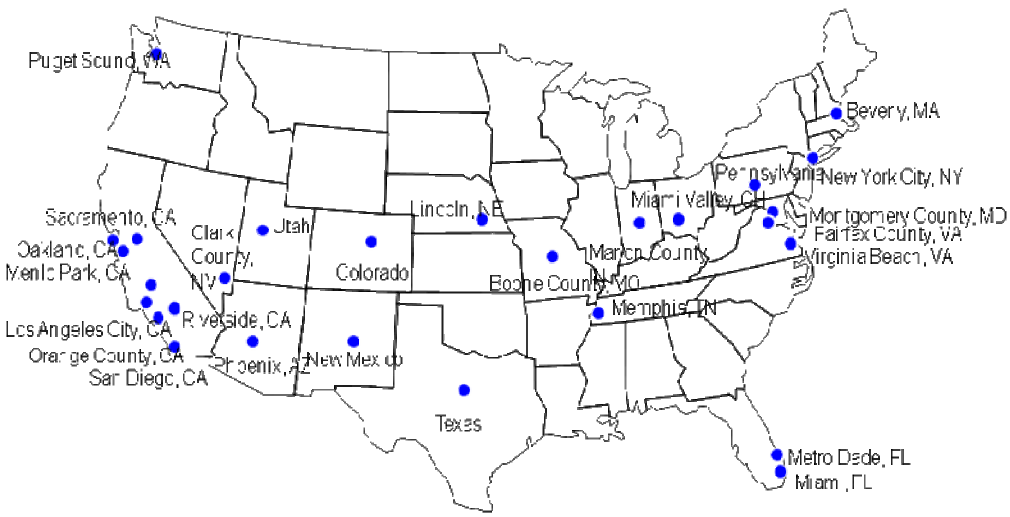

Figure 1: DHS/FEMA Task Forces

DHS/FEMA Urban Search and Rescue Task Force

The current DHS/FEMA Urban Search & Rescue Task Force (Figure 2) consists of 70 persons divided into six teams: Search, Rescue, Hazmat, Medical, Logistics, and Planning. The team is led by two Task Force Leaders. There are two Safety Officers who report directly to the Task Force Leaders. The Task Force is designed to operate in two 12-hour shifts and to be completely self-sufficient for 72 hours.

The Task Force is expected to be committed for an operational period of 10 days and to be re-supplied and supported by other DHS/FEMA and other federal agencies. Each member of the Task Force must meet basic US&R requirements for experience and training and must be fully qualified and trained in his or her own specialty area. Cross-training is strongly encouraged. When not activated as part of the National Response Framework (Federal US&R Response), the Task Force can be used by the sponsoring jurisdiction for local emergency work deployed either as a subset team or as a full Task Force.

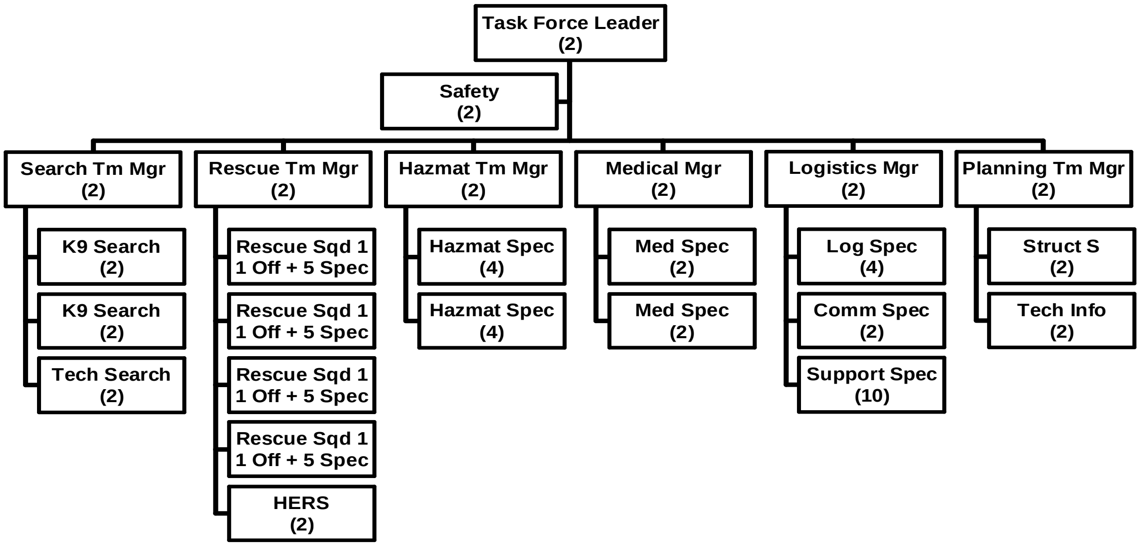

Figure 2: Configuration of Type 1 DHS/FEMA US&R Task Force

Task Force Training

Response preparedness and readiness requires significant training for all US&R Task Force members. There are requirements for basic training for each member such as First Aid, Incident Command System, Basic Rescue, Hazardous Materials, etc. Technical training is also required for each specialist on a Task Force, and the Task Force must undergo team training designed to foster cohesiveness and unity of purpose.

Since the beginning of the US&R program, FEMA charged the Working Groups in the areas of Search, Rescue, Medical, Logistics, Communications, and Technical (engineering, heavy rigging, and hazardous materials) to survey existing internal and external training resources and identify the strengths and shortfalls. When training deficiencies were identified, actions were taken to either develop the needed course by the Working Groups or place a contract for development with an appropriate source.

Beginning in April 1992, FEMA conducted six Orientation Training sessions across the country. These 4-day sessions were designed to prepare a Task Force to operate as part of the National US&R System and focus on the Federal Response Plan (National Response Framework). The meetings emphasized agency responsibilities and Task Force operations. Participants included Task Force Leaders, Team Leaders, Technical Specialists, and Department of Defense Liaison Officers. Other training courses that have been developed are:

- Crush Syndrome/Confined Space Medicine Training (FEMA contract);
- Communications Training (developed by the Boise Inter- Agency Fire Center);
- Structures Specialist Training (developed by the U.S. Army Corps of Engineers);
- Advanced Structures Specialist Training (developed by the U.S. Army Corps of Engineers);
- Canine Search Training (developed by Search Working Group);

- Logistic Specialist Course (developed by Logistics Working Group); and
- Advanced Rescue Specialist Training (developed by Rescue Working Group to conform to NFPA 1670[1]).

Engineers Participation in Disaster Response & DHS/FEMA US&R

In the late 1970's, Disaster Services Committees (DES) were started in California by both the American Society of Civil Engineers (ASCE) and the Structural Engineers Association of California (SEAOC). The focus of these groups was to develop and organize the response of engineers to aid building departments in post earthquake safety evaluation of damaged structures. Engineers volunteered in this capacity following the Coalinga earthquake in 1984, and this activity has become a vital part of the planned response to earthquakes in California. The Applied Technology Council publication ATC-20, Procedures for Post-Earthquake Safety Evaluation of Buildings, funded in 1989 by the Offices of Emergency Services from the State of California (CAOES) and FEMA, was developed as the standard for earthquake response. Many engineers throughout the U.S. have been trained under ATC 20 for a post-earthquake volunteer response.

After the Mexico City earthquake experience, a few engineers perceived the need to work within the firefighter rescue community in order to enhance their knowledge and capability in dealing with heavy, complicated collapsed structures. Through the National Association for Search and Rescue (NASAR) and a California based non-profit group, Urban Search and Rescue, Inc., discussions and training sessions were conducted in an attempt to add to the knowledge base regarding collapsed structure operations.

In 1990, these engineers became members of FEMA's US&R Advisory Committee and Working Groups, thereby contributing to the development of the National Urban Search & Rescue program. Shortly thereafter, the U.S. Army Corps of Engineers (USACE) sponsored the development of the initial Structures Specialist Training Course (StS1). This course was designed to train both engineers from USACE as well as civilian engineers who would become Task Force Structures Specialists. The first course was presented in 1992 and there has been at least one Structures Specialist course offered every year since.

There are two Structures Specialists on a Task Force (one for each 12-hour shift). A Task Force is required to have three 70-person teams available for deployment. Therefore, there are at least six Structures Specialists required per Task Force, each trained in both US&R operations and collapsed structures operations. Experience over the years has shown that the Structures Specialist is a critical position within the Task Force and additional training is warranted. The Technical Working Group developed and USACE sponsored a second course, Advanced Structures Specialist Training (StS2), with the first offering occurring in 2004. In 2007, USACE started offering yearly Special Skills training for the Structures Specialists in each of the three DHS/FEMA US&R regions.

Since 1992, over 400 engineers have successfully completed the StS1, Structures Specialist course with many of them also completing StS2, Advanced Structures Specialist and Special Skills, Regional Training courses. Over 400 Structures Specialists have been trained to respond

[1] National Fire Protection Association Standard on Operations and Training for Technical Search and Rescue Incidents

to a collapsed building incident with a DHS/FEMA Task Force, as part of a USACE response, or as part of a state Task Force.

DHS/FEMA Task Force Response

After a significant disaster incident, a Presidential Declaration of a disaster activates the National Response Framework. This activation may be for the entire plan (all types of resources) or only those Emergency Support Functions that may be needed for an organized response. If the nature of the disaster is such that US&R capabilities may be required (ESF 9), DHS/FEMA will place selected Task Forces on alert. Once the need for US&R assets is confirmed, the Task Forces are activated and have 6 hours to fill the positions billet, cache and package the equipment and move to a designated Point of Departure. The Task Force is then transported to a Mobilization Center near the site of the disaster. Once on site, operational control of the Task Force passes from DHS/FEMA to the local Incident Commander. The Task Forces on site are coordinated by the DHS/FEMA Incident Support Team (IST). The DHS/FEMA IST and Task Forces would continue to be supported by DHS/FEMA assets.

DISASTER SITE MANAGEMENT AND PLANNING

During all phases of a structure collapse incident, there will be some sort of an Incident Action Plan. For the initial incident commander (local fire as mentioned in the previous section), the plan may not be a written document, but it would include gaining control of the site (and all utilities), mitigating the obvious hazards (putting out fires, etc.), identifying collapse extent and falling hazards, and setting up command and staging areas.

Following the initial chaotic phase (that may last for 12 to 24 hours), the Incident Commander (IC) would develop the operation plans for the incident. A more organized response would evolve as a schedule of operational periods is initiated and the IC issues the first Incident Action Plan. As part of the Incident Command System process, a Planning Team would work with the IC to generate updated action plans for each operation period as operations progress. Incident planning is a critical tool for improving the efficiency, accountability, communication, and risk reduction at a structure collapse incident.

Participating agencies, such as the DHS/FEMA Incident Support Team (DHS/FEMA IST), use the Incident Action Plan to develop Operational Action Plans for their contribution to the response. The DHS/FEMA IST coordinates the Task Forces on site and assigns duties from the Incident Action Plan. The Task Forces develop a Tactical Action Plan for their operations during the operational period. Thus, there are three action plans developed for each operational period:

- Incident Action Plan
- Operational Action Plan
- Tactical Action Plan

Incident Action Plan

The Incident Action Plan is developed by the Incident Command staff (or IC in a small incident) and defines the broad objectives that need to be accomplished during the next operational period. The contact information for all participants is included and special emergency information would be included.

Operational Action Plan

The Operational Action Plan is developed by participating agencies such as the DHS/FEMA. For a building collapse, it would be developed by the DHS/FEMA Incident Support Team and would define what the DHS/FEMA US&R Task Forces need to accomplish during the operational period. It would also include important contact information (radio frequencies, etc.) as well as information on special hazards. It could also include information about structure and atmospheric monitoring and other mitigation that had been previously implemented.

Tactical Action Plan

The Tactical Action Plan is developed by the Task Force (or on site working team) and it defines the specific tasks to be accomplished during the operational period. It would also include communication information for within the team unit, and monitoring and other mitigation data that would be handed off from previous operational periods.

URBAN SEARCH & RESCUE RESPONSE AT A COLLAPSED STRUCTURE INCIDENT

Although every collapsed building disaster is unique in its type and magnitude and in the response, this section describes aspects of the atmosphere and response at a "typical" disaster site. In most all structure collapse incidents, the first response will be by a local fire department unit, who will set-up the initial command. They will do their best to control the site and keep bystanders away, but they must focus on the possibility of trapped victims. If the need for response is large, additional mutual-aid will be requested. For a major incident, state and/or federal assistance may be needed (Figure 3). If federal help is required, the Governor from the affected state will request the President to Declare a Federal Disaster and the National Response Framework (NRF) may be activated.

This was the case following the 1995 bombing of the Murrah Building in Oklahoma City and the Pentagon Incident on 911. The 911 World Trade Center disaster was somewhat more complex with the Fire Department of New York maintaining command, but the NRF was activated.

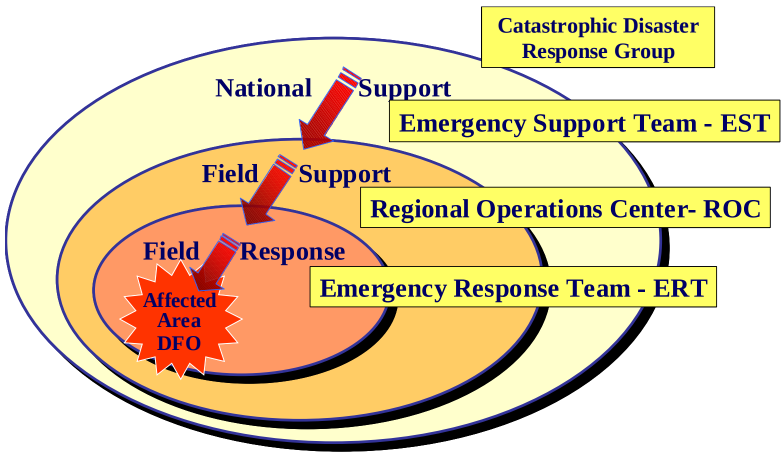

Figure 3: Federal Response Focused on a Specific Disaster Site

If all involved have been trained in the use of the Incident Command System (ICS), the resource build-up can occur in an efficient and timely manner. The Incident Command in most all cases will remain under the authority of the local authorities, and many different agencies (federal, state, and local) can be integrated into the overall response. ICS has been universally adopted by response systems throughout the U.S. since it is flexible and allows for the integration of many different types of agencies into all types of incidents. ICS also allows the defining of many different functions and specifying a realistic span-of-control system

For a collapsed structure incident, the DHS/FEMA Response System has set standards for equipping and training Urban Search & Rescue units. Therefore, teams from the DHS/FEMA System, as well as state and local teams, can work side-by-side and conduct equally efficient operations. The rescue trained professional engineer (Structures Specialist) needs to be integrated into the response as a trusted member of a US&R Task Force or other response agency. This allows the Structures Specialist to effectively conduct time-critical hazard assessments and recommend hazard mitigation plans that best fit search and rescue operations. At the start of an incident, Urban Search & Rescue operations have a single objective: to save live trapped victims. Eventually after some time, the objective may change to recovery of deceased victims. The acceptable risk to response personnel changes dramatically between these two objectives and the US&R team must be conscience of Risk vs. Reward during all operations.

Disaster Site Hazards and the Risk vs. Reward Mentality

Following a structure collapse, the initial local volunteer responders will enter dangerous situations if there is the possibility of aiding and removing live victims. Although these volunteers may be helpful, they may not have proper protective equipment and they themselves may become victims. Soon after this initial response from local volunteers, a local incident commander (local fire) will take control of the site. A knowledgeable commander will make a quick assessment of the situation and call for aid if it is required. This aid, at a minimum, will include law enforcement to maintain control and secure the site.

The initial incident commander’s immediate actions will be to:

- Control all site utilities;
- Determine collapse and falling hazard zones;
- Determine potential number of trapped victims;
- Setup command location and staging areas;
- Plan how best to control rescuers and bystanders; and
- Determine need for additional resources.

If the incident is of the size where trapped victims are probable, then many types of aid will be requested including Special Operation Rescue Units that are more skilled in the use of tools that may be used to extricate victims. For very large incidents, state and/or federal support may be requested, and the incident may go through the following phases:

- Reconnaissance/assessment, search, and prioritization;
- Light rescue with minimal mitigation;
- Heavy rescue with selected debris removal and extended mitigation;

- Body recovery; and
- Demolition.

The first three phases are usually called the Rescue Phase, when greater risk may be taken if there is a chance of saving a live trapped victim (high reward). Body recovery normally would be completed after the incident has transitioned to the Recovery Phase, when risk to rescue personnel should be minimized (low reward). Demolition would normally be done by contractors, using heavy equipment, but in some cases there may still need to be some bodies recovered during this phase. Each phase will be discussed below.

Reconnaissance/Assessment, Search, and Prioritization

For an incident that involves a single or a few structures, search proceeds (using personnel, inserted cameras, electronic detectors, and canine) to determine if viable victims are present. The Structures Specialist performs an assessment to identify falling and collapse hazards in order to advise the searchers on (1) the level of risk and (2) alterative techniques to minimize risk. During this phase significant risks would be taken since the “Reward” of saving lives is high.

If viable victims are located, then a plan is developed to prioritize the rescue effort relative to the risk. As victims are removed from the least risky locations, other rescue teams would be working on mitigation measures that could reduce the risk in other areas. The objective of the Structures Specialist during this phase is to suggest alternatives for mitigation of risk (hazards), with the emphasis on mitigation that can be implemented quickly

For an incident that involves many structures (such as a large earthquake), a pre-prioritization process (Rapid Recon) would identify structures according their potential for having viable victims and the relative level of risk associated with each structure. Search teams would be directed to the most favorable structures first to determine number and location of viable victims. This process might continue for many hours until all the structures were prioritized. A Structures Specialist (as well as a Hazmat Specialist and a Rescue or Search Team Leader) would be part of the Rapid Recon Team. Rescue teams would start operations in the highest priority sites.

At each of the buildings where viable victims were located, the Structures Specialist’s responsibilities would be the same as for the single building incident discussed above. This would also be a High Risk, High Reward operation.

Light Rescue with Minimal Mitigation

Light rescue operations would start (as described above) as soon as viable victims were located. The victims may not be trapped too badly and a quick airbag lift, or the cutting/removal of lighter debris, would free them. The victims would be medically stabilized and extricated according to the severity of their injuries. The mitigation measures that would be used to reduce risk would be avoidance, hazard removal, minimize exposure time and number of rescuers, or installation of spot shores and localized cribbing. Mitigation methods are described in a companion paper, Hazard Assessment and Mitigation Techniques for Explosion Collapsed Buildings.

The rescuers that enter a confined space would (in at least the case of an earthquake incident) be prepared for the possibility of secondary collapse. The minimum safety requirements upon entering the space would be to have an accountability system including verified voice or radio communications, identifying the preferred escape route, and identifying or building safe havens within the collapse zone. There would also be a Rapid Intervention Team available outside of the confined space in case the rescue team experiences difficulty. In this way risk would be reduced, but this would still be a high risk, high reward operation.

Selected Debris Removal and Extended Mitigation

Once the more easily accessed victims have been removed, the incident moves into a phase where risk should be significantly reduced. This would involve victims who are considerably trapped or pinned in debris. Rescue personnel may work in confined spaces for many hours to reach each victim. The operations may even proceed for many days and involve the removal of deceased victims.

Wall breaching, structural element cutting or removal, or heavy lifting may be required to access victims. Shoring may be required to provide alternate and redundant load paths for the damaged structure to reduce operation risk. Shoring is discussed in a companion paper, Shoring Stabilization of Buildings in an Urban Search & Rescue Environment. The Structures Specialist would be heavily involved in designing the shoring plan and in suggesting alternate methods of mitigation.

Body Recovery

When the incident switches from rescue of live victims to recovery of deceased victims, the assumption is that no viable victims remain and rescue personnel should not take unnecessary risks. The numbers of rescue personnel on site would be significantly reduced, and demolition contractors, using heavy equipment would begin deconstruction. This work would need to proceed slowly if there were deceased victims known to be still entombed, or if there were still some missing individuals.

Rescue personnel may need to be used as spotters so that if victims are found they may be carefully removed with dignity. The Structures Specialist would be asked to recommend the mitigation measures that would reduce risk to as low a level as reasonable, bearing in mind that the operation of heavy equipment has special risks.

Summary

When there is a major incident that involves building collapse, local authorities are neither trained nor equipped to conduct search and heavy rescue operations. The hazards and risk to response personnel are high, and local authorities are oftentimes overwhelmed. The United States has developed the National Response Framework to supplement local authority assets for Urban Search & Rescue operations. This paper describes the history of the current DHS/FEMA Urban Search & Rescue system and how it works with federal agencies and the local authority to search for and rescue victims of a collapsed building incident.

Hazard Assessment and Mitigation Techniques for Explosion Collapsed Buildings

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ABSTRACT

At a structural collapse incident, the Structures Specialist (a specially trained civil/ structural engineer) is tasked with evaluating the damaged structure and identifying hazards to rescue personnel as they operate in the building. Search and rescue operations in a structural collapse can present high risk to personnel in and around the incident. The Structures Specialist evaluates the damaged structure and identifies hazards to rescue personnel as they operate in the building. Although much of this paper discusses these issues for all types of collapse incidents, building collapse from explosions is emphasized.

INTRODUCTION

There are many events that may initiate structural damage and collapse, requiring search and rescue efforts. These include earthquakes, wind events, landslides/debris flows, floods/tsunamis, fire, high energy impacts, industrial accidents, structural defects and overloads, and explosions. Regardless of the initiating incident, the responding Structures Specialist (a specially trained civil/structural engineer) is tasked with evaluating the damaged structure and identifying hazards to rescue personnel as they operate in the building.

This paper presents an overview of the procedures and techniques developed and used by the Department of Homeland Security Federal Emergency Management Agency's Urban Search & Rescue program for collapsed building hazard identification, assessment, and mitigation. The paper first discusses these issues for all types of collapse incidents, then presents special considerations in post-explosion environments.

HAZARD IDENTIFICATION IN DAMAGED STRUCTURES

In damaged, partially collapsed, and collapsed structures there are three primary types of hazards that are of concern for rescue personnel:

- Overhead Falling Hazards: parts of the structure or its contents are in danger of falling;
- Collapse Hazards: survivable void spaces may become unstable during the operation; and
- Environment Hazards: toxic or flammable gases, low oxygen environments, etc.

Falling and collapse hazards are significant concerns. The degree of risk in both falling and collapse hazards strongly relates to mass and determining how additional movement or failure may occur. Recognizing falling hazards is typically as simple as looking around the damaged structure. Sometimes, perceived falling hazards are so integrated into the damaged structure that the risk of detachment is relatively small, see Figure 1. Small, nonstructural elements and debris (loose materials) may be greater direct hazards to personnel working on the area than overall structural stability.

Figure 1: Monitoring potential falling hazard at the WTC '01

Progressive collapse scenarios must be recognized early in the rescue operation. The potential for progressive collapse depends on the type of structure, building materials, method of construction, and assessment of its failure mode and affects. Brittle, sudden failure potential must be recognized as opposed to structures in which material ductility and redundant configurations could provide some warning of an additional collapse. The problem of identifying, let alone properly evaluating, these hazards, is overwhelming. A well trained Structures Specialist may, at best, be able to rate the risk of various hazards on an arbitrary scale of low risk, moderate risk, and high risk.

In the structural collapse rescue environment, there are no hazard-free or "safe" structures. The Structures Specialist evaluates situations ranging from dangerous to extremely dangerous. One must recognize that engineering judgments at a structural collapse incident cannot be precise.

Partial collapses are very difficult to assess, and it is difficult to predict future behavior. If a damaged structure is currently at rest, the Structures Specialist could conclude that the collapsing structure had met enough resistance to stop moving and had come to an “At-Rest” condition. Without new demands, the structure could be assumed to be stable; however, the damaged structure is clearly more disorganized than the original as-built condition. The partially collapsed building is weaker than it was in the original condition, and certainly is very difficult to assess. The Structures Specialist must identify the current load paths, remaining structural capacity, levels of redundancy, and forms of ductility. Brittle, sudden failure potential must be recognized immediately, as these conditions can lead to sudden catastrophic progressive failure of the building.

HAZARD IDENTIFICATION FOR SPECIFIC TYPES OF BUILDINGS

The following discusses the typical falling and collapse hazards for five types of buildings. The discussion includes the expected hazards and behavior when the buildings are subject to all types of extreme events such as earthquakes, windstorms, flooding, and explosions. For explosions exclusively, the expected hazards and behavior would be a subset of those described and shown in the figures.

The types of buildings discussed here are:

- Light Frame: mostly wood frame and pre-engineered light steel buildings;
- Steel Frame: either moment frame or diagonally braced frame buildings.
- Heavy Wall: unreinforced masonry, tilt-up, and other low-rise buildings with concrete and masonry walls;
- Heavy Floor: concrete frame buildings; and
- Precast Concrete: fairly heavy floors and some heavy walls.

Light Frame Buildings

Figure 2 illustrates typical hazards in a multi-story light frame wood building. The principal weakness is in the lateral strength of walls and connections. In structures of less than three stories, additional collapse is unlikely because of the light weight of this type of construction. Additional collapse of this type is often slow and noisy. Falling masonry chimneys and masonry veneers are the most brittle types of behavior for these structures. The hazard identification check points are:

- Badly cracked or leaning walls;
- Offset residence from foundation;
- Leaning first story in multi-story buildings;
- Cracked, leaning masonry chimney or veneer; and
- Separated porches, split level floors/roof.

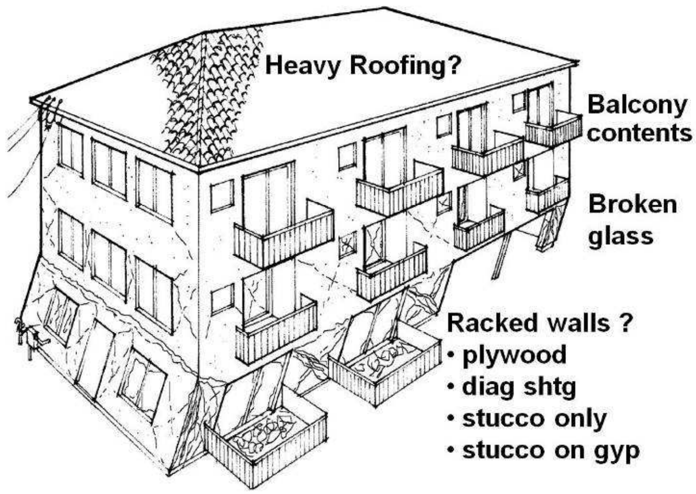

Figure 2: Light Frame Building

Steel Frame Buildings

Figure 3 illustrates typical hazards in a damaged heavy steel frame building. The principal concerns are the potential for building cladding to become falling hazards, and the cracking of welds in the main moment resistant connections. Both of these hazards have occurred during earthquakes. Following earthquakes in 1985, 1989, 1993, and 1994, building codes now require improved ductility in both the cladding attachments and the moment resistant connections. The hazard identification check points are:

- Exterior cladding for leaning or broken connections;
- Indications of movement—plumb corners, stair and non-structural damage—as clues to potential structure damage;
- Main Beam-Column connections—may need to remove finishes or fireproofing; and
- Broken/damaged floor beam connections and, if present, broken PC slab connections.

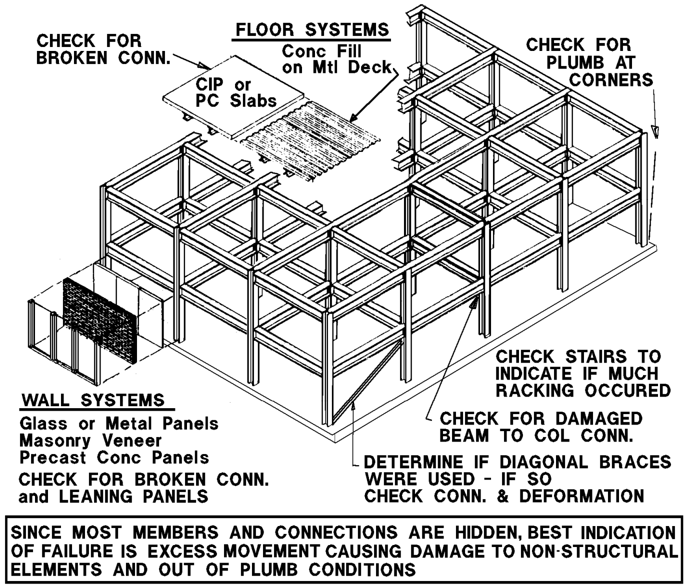

Figure 3: Steel Frame Building

Heavy Wall Buildings

Figure 4 illustrates typical hazards in a damaged heavy masonry wall building. The principal weakness is in the lateral strength of walls and their connections to floors/roof. Falling hazards are common in unreinforced masonry buildings because of the combination of weak and heavy wall elements. Collapse of adjacent buildings can occur as a result of the falling hazard of party walls. All additional failure will probably be brittle. The hazard identification check points are:

- Loose, broken parapets and ornamentation;
- Connection between floor and wall;
- Cracked wall corners, openings;
- Peeled walls (split thickness); and
- Unsupported and partly collapsed floors.

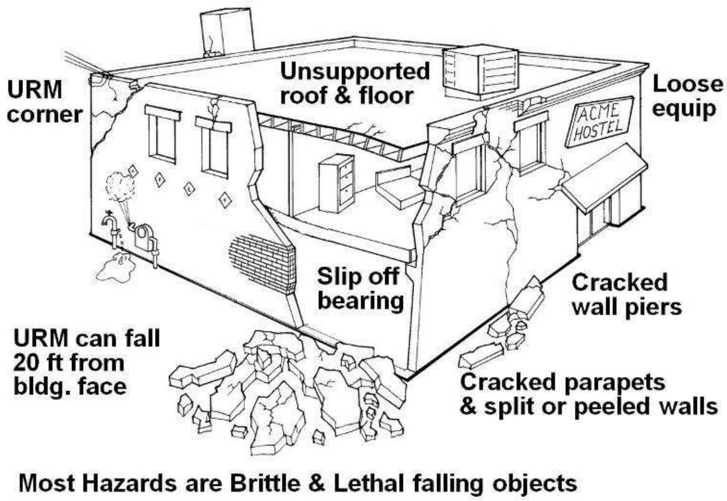

Figure 4: Heavy Wall Building

Heavy Floor Buildings

Figure 5 illustrates typical hazards in a damaged heavy floor concrete frame building. The principal weakness is both a lack of adequate column reinforcement that can properly confine the concrete and an inadequate connection between slabs and columns. Ductile behavior may still be possible if the concrete is confined by reinforcing and the reinforcing is still elastic. The hazard identification check points are:

- Confinement of concrete in columns (empty basket);
- Cracking of columns at each floor line (above and below floor);
- Diagonal shear cracking in beams adjacent to supporting columns and walls;
- Cracking in flat slabs adjacent to columns;
- Attachment of heavy non-structural, unreinforced masonry walls (infill walls); and
- Cracks in concrete shear walls and/or stairs.

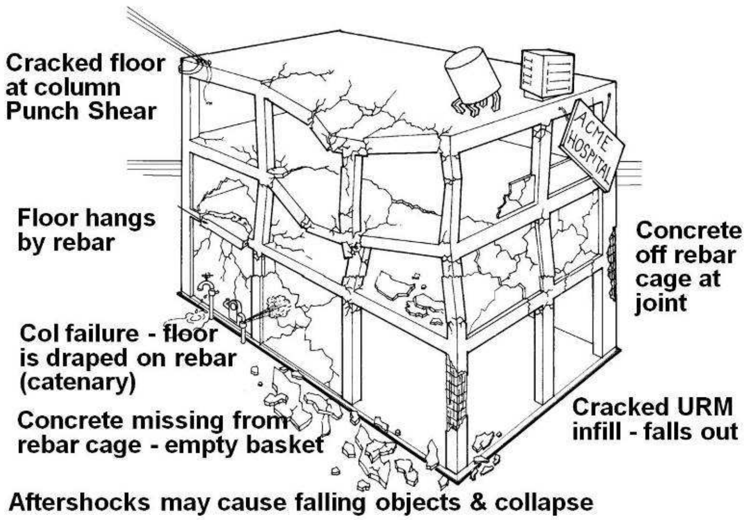

Figure 5: Heavy Floor Building

Precast Concrete Buildings

Figure 6 illustrates typical hazards in a damaged precast frame building with infill panels. The principal weakness is the interconnection of parts: slabs to walls/beams, beams to columns, walls to slabs, etc. It is very difficult to make connections adequate enough to transfer the strength of parts, connections adequate to survive a maximum earthquake. These buildings can have fairly heavy walls and floors, but neither is as heavy as heavy wall or heavy floor types. These structures are often made from lightweight concrete, which splits more easily than normal weight concrete. Most failures that occur due to broken connections will be brittle. Since individual building parts may be quite strong, cracked concrete failures may be ductile if adequate bonded reinforcing is present. Depending on extent of collapse, many falling hazards may be present. The hazard identification check points are:

- Beams to column connections, broken welds, and cracked corbels;
- Column cracking at top, bottom, and wall joints;
- Wall panel connections;
- Shear wall connections at floors and foundation; and
- Badly cracked walls.

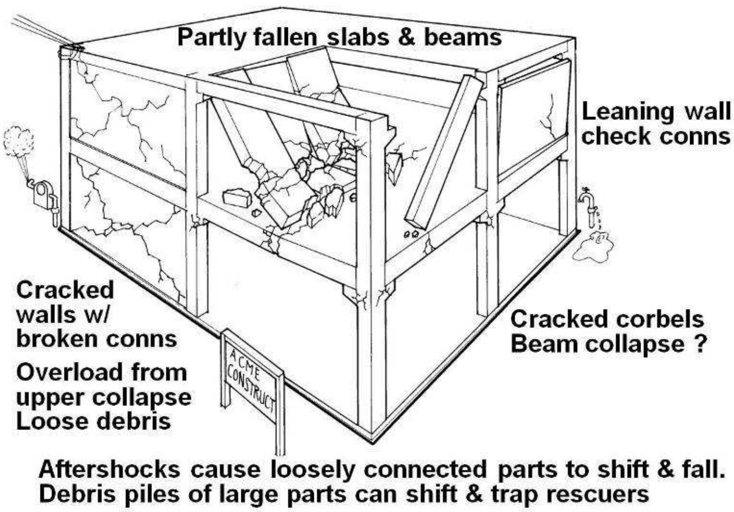

Figure 6: Precast Concrete Building

In summary, identifying hazards after a structural collapse is extremely difficult. Buildings are often complicated, and there are many different types and configurations. What remains after the triggering event may have come to rest, but the danger of further collapse and/or falling objects is often present. A damaged structure may be “At-Rest,” but that does not mean that it is “Stable.” A properly trained Structures Specialist can help identify these hazards. Measures to mitigate the danger can then be factored into the overall rescue effort.

HAZARD ASSESSMENT FOR RESCUE OPERATIONS

Based on the previous section on Hazard Identification, the next step is to assess the risk to personnel during rescue operations. Assessment applies to the building structural system, the rubble pile, and individual void spaces. The first question should be, “do we need to be in this area at all?” If the answer is no because the likelihood of locating survivors is extremely low, then simply avoid that area. Hazard avoidance is the preferred option. Additional questions the Structures Specialist will consider are:

- What caused the collapse? Aftershock, wind, explosion, unknown?
- Has the structure collapsed to a stable condition? Does the structure have remaining stored potential energy?
- How have the load paths changed due to the collapse?
- Will the structure exhibit brittle or ductile behavior?
- Are there potential instabilities in the building or in the rubble?
- What redundancy is present? Where is the fuse in the structural system?
- What if there is an aftershock?
- What are the operating objectives of the Incident Action Plan (IAP)?
- If personnel are to enter a hazard area, where are the escape routes and/or safe havens?

- Are there overhead or leaning wall falling hazards?
- How can the hazards be mitigated to an acceptable level of risk for the rescuers?
- Can we provide additional mitigation measures to reduce the potential for secondary collapse while limiting the significant risk associated with providing the mitigation?

The Structures Specialist compiles the results of the hazard identification process, assimilates it with his/her knowledge of building behavior and performance, and develops a mitigation plan to help manage rescue operations risk. The plan will include the arbitrary consideration of risk vs. reward. If there are confirmed live victims trapped in the collapsed structure, slowing the rescue operation with time-intensive mitigation efforts is not usually an acceptable alternative to the incident commander. The rescuers are willing to accept more risk for the benefit of saving a life. However, if the victims are expected to be deceased, then the acceptable risk to personnel in the recovery effort is much lower, and more effort can be extended to hazard mitigation.

STRUCTURAL HAZARD MITIGATION PLANNING

Following hazard assessment, alternatives need to be considered that will reduce the rescue operations risk to an acceptable level. The Structures Specialist significantly contributes to the development of a prioritized hazard mitigation plan. This mitigation plan must be developed very quickly for it to be useful to the rescue operations and integrated into the IAP. The mitigation plan may start as nothing more than rough sketches and transition into something much more descriptive and formal. Eventually, a written plan will be developed that will become part of the IAP. The mitigation plan is typically revised and improved as the incident progresses.

At least some risk is involved in most all rescue operations. In addition, many of the most viable mitigation options involve risk during their installation. The Structures Specialist must consider and clearly state the mitigation installation risk in the mitigation plan. Obviously, the lowest risk mitigation options should be considered first. These usually include the mitigation options that require the least time to install or implement, such as avoiding the hazardous area.

If live victims are located, their survival may depend on the speed with which they are removed from the collapsed structure. There may not be time to construct well-braced shoring systems or other elaborate mitigation methods. Accordingly, the acceptable risk level for emergency personnel is higher and rapidly deployable mitigation methods are essential. The Structures Specialist must be as innovative as possible in order to find a balance between the desired risk reduction and the time it takes to implement the mitigation.

STRUCTURAL HAZARD MITIGATION OPTIONS

There are several options available to reduce risk and expedite rescue of victims. Generally, the five main options are to AVOID, REMOVE, MINIMIZE EXPOSURE, MONITOR, and SHORE the hazards. Other methods (not described here) for special purposes are SHIELDING, LATERAL BRACING (of unsupported columns and beams), and TIEBACKS. Following is a brief description of each of five general mitigation methods that can be implemented to reduce risk during rescue operations.

Avoid the Hazard

If there is no immediate need to be in a specific dangerous area, that area is cordoned off and personnel do not enter the hazard zone. The hazard is thus avoided. An example would be to rope off the front of a building where there is collapse debris that could slough off the building or a parapet that is subject to falling. Another example is to access a badly collapsed structure from the top rather than from the edge (between layers). The Structures Specialist should consider alternatives to hazardous situations, consult with others, and be as resourceful as possible.

Remove the Hazard

One of the most dangerous situations for rescuers is falling debris or overhead objects. By removing the object, the hazard can be removed. Another example is a leaning non-load-bearing wall or a leaning brick chimney. After considering the effects of the removal itself, the wall or chimney can be pulled down, removing the falling hazard in the operation's area. Other examples include removing parts of unreinforced masonry walls by hand, using aerial ladders for upper portions, or for larger pieces, using a crane and clamshell. Precast concrete sections are more easily removed by small cranes or other concrete removal machines due to their moderate size and lack of interconnections. If at all possible, lift-off, push-over, or pull-down (safely of course) should be a first choice.

Minimize Exposure to the Hazard

When time is critical, or other hazard reduction methods are not justified, the risk can be reduced by minimizing exposure of personnel to a dangerous area. For instance, if a large building is racked laterally, shoring that building would require much time, effort, and materials. If there are live victims in the structure, rescuers can minimize the number of personnel in the building, minimize the time spent in the building, and avoid the higher risk areas in the building. Risk is a function of both hazard severity and exposure (time). Another example is if there is a victim trapped in a building and the time for extrication is estimated to be short. Then the time required to shore the building may not justify the short exposure time for the rescuers to extricate the victim. Reduced risk can be achieved by locating safe havens and emergency egress routes in case of trouble.

Shore the Hazard

The most costly in terms of personnel resources, material resources, and time resources is mitigating the hazard by stabilizing the structure with shoring. When there is considerable risk to rescue personnel and the rescuers will need to work in the high risk area for a significant amount of time, shoring stabilization of the structure is warranted. Shoring is also warranted when the reward is low (recovery vs. rescue). Shoring can also be used to provide rescue personnel with safe havens and emergency egress routes. A companion paper, Shoring Stabilization of Buildings in an Urban Search & Rescue Environment, presents effective shoring techniques, objectives of shoring, and experimental testing of shoring systems.

Monitor the Hazard

Monitoring the time dependent movement of a structure as operations continue comes in many forms including using surveying equipment to monitor building movements, strain gage indicators to monitor crack widths, digital levels to monitor plumbness or rotations of walls or components, wireless rotation sensors for monitoring dangerous areas, and others, some as simple as a plumb bob. Monitoring can be used to track global building movement, element or component movement, debris field movement, or very localized area movement. Monitoring can be used independently or in conjunction with other forms of hazard reduction methods. To be effective these devices must be continually read and accompanied by an effective alarm system that activates an efficient evacuation plan. Monitoring is usually quick to set up and does not require significant resources.

SPECIAL CONSIDERATIONS IN POST-EXPLOSION ENVIRONMENTS

An explosion is a rapid release of energy that manifests in the forms of light, heat, and a shock wave, with the shock wave generating the majority of structure damage and human injury. The shock wave expands radially outward from the source and imposes extremely high pressures (often orders of magnitude larger than design basis loading), for short durations (measured in milliseconds) on structures in its path.

There are many factors that determine the damage and injury patterns from explosions, these include

- Net explosive weight
- Distance from the explosion
- Building construction type/structural configuration
- Building envelope configuration

The net explosive weight (NEW) and the distance of the building elements from the explosion are the primary determinants in the magnitude and duration of the load that is applied. If building elements are close to the explosion, the first damage mode will be brisance or breach of the material, which essentially shatters the building elements with such force that concrete can be completely blown away, leaving nothing but reinforcing steel. For building elements farther from the explosion, the primary failure modes will be flexural and shear failures.

Explosive forces affect materials and structural configurations differently, with damage modes being affected by material mass, redundancy, connection integrity, and surface/tributary area of the loaded elements. Occupied structures are typically designed for gravity-based dead loads and live loads. However, in explosions, large, weak, and/or lightly attached wall, floor, and roof surfaces may be loaded asymmetrically and in different directions from the original design basis. This atypical load case can lift slabs and blow away load bearing walls and columns.

The various building systems will respond differently to an explosion. The columns and beams in steel frame structures may survive the blast, but their stability may be compromised by the removal of their lateral bracing elements (floors, shear walls). In large explosions, concrete slabs, walls, and even columns may be catastrophically failed or severely compromised, leading to conditions that destabilize a structure to the point of actual or incipient progressive collapse.

In the case of an exterior explosion, the shock wave is initially reflected and amplified by the building face and then penetrates through openings, subjecting floor and wall surfaces to great pressure. Finally, the entire building is engulfed by the shock wave, subjecting all building surfaces to the over-pressure.

Building envelopes can provide protection for building interiors and occupants if they are able to resist the applied forces, thereby limiting debris and decreasing pressures entering the occupied spaces. However, building envelopes (unless they are specially designed for blast resistance) are rarely able to resist these forces, and they therefore become flying debris during an explosive event and become overhead hazards during evacuation and rescue operations.

Figures 7 through 9 show the blast effects of the 1995 bombing of the Murrah Building in Oklahoma City. When large surfaces are engaged by blast pressures, they will be deformed as the shock wave passes, but the direction of the net force will be determined by the complexities of the wave path and time. The walls and floors in frame designed structures, as well as box buildings, have large surfaces that will receive high blast forces. They can be ripped away from their connections, leading to the partial or total structural collapse. The explosive pressure may thrust the building floors upward (contra-normal loading), fail the floor, then initiate collapse into a dense rubble pile. Heavy columns tend to survive the blast, but the lighter floors that load and laterally support them may be consumed by the blast. Steel frames, beams, and columns may also survive but will be compromised by failed or missing bracing. Specific types of buildings resist blast loads in various ways and the Structures Specialist needs to understand the different behaviors to correctly assess the damage and recommend hazard mitigation plans.

Figure 7: Murrah Building After the Oklahoma City Bombing

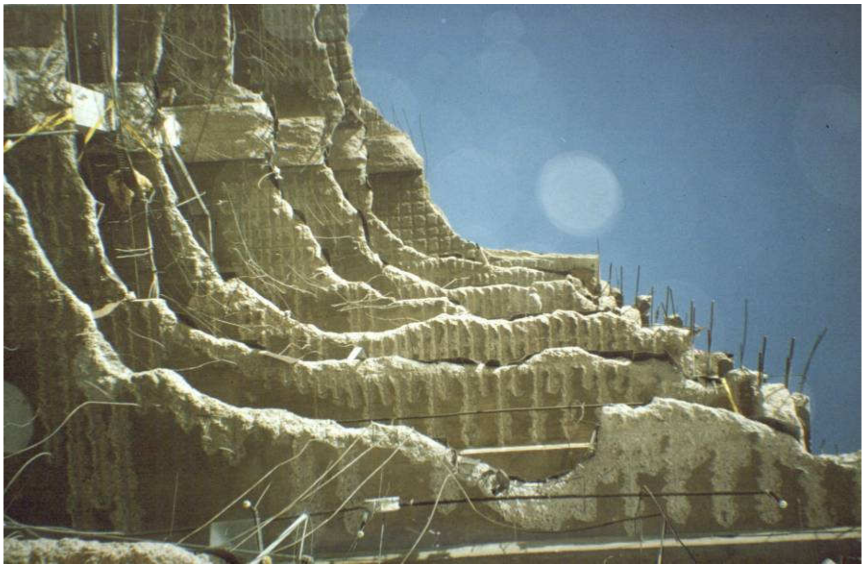

Figure 8: Murrah Building Floor Slabs (looking up) Missing Slab-Reinforcing Steel

Figure 9: Murrah Building Search and Rescue Operations

EXPLOSION EFFECTS ON SPECIFIC TYPES OF BUILDINGS

The following is a brief description of the most predictable blast damage for the building types presented in previous sections.

Light Frame Buildings

Wood buildings are considered light framed buildings. These structures are considered flexible. The light wall and roof planes can be blown away and/or shredded. Leveling of all or at least a significant part of the structure can occur. The lighter building materials which are blown away reduce the explosive pressure wave reflections within the structure.

Light metal buildings would also behave like light framed buildings. The light metal roof and wall panels can easily be blown away, leaving a bare, poorly braced frame. Roof purlins and wall girts normally have relatively light connections and may be ripped away with the metal panels. The frames may collapse from lack of lateral support and/or push from the blast pressure. The result can be a completely collapsed pile of bent and twisted steel members.

Steel Frame Buildings

A well-designed steel frame structure may be more resistant to explosions since the structural steel frame, comprised of beams and columns, is constructed to have both upward and downward strength. These structures usually have robust welded or bolted connections. Floor systems could be lightly reinforced concrete decks or bar joists. The floor systems may separate from the supporting beams as the pressure wave passes through. The most likely scenario is for at least part of the frame to remain, but beams may be twisted, with large areas of the floor diaphragm missing. The floors lift from the blast and then drop from their gravity weight. A rubble pile ensues under the collapse area.

Heavy Wall Buildings

Tilt up concrete, reinforced masonry, and unreinforced masonry wall buildings have heavy walls and relatively light floors. The structural stability of these structures depends on the floor to wall connection integrity. Blast pressures will tend to engage the wall and roof surfaces, severing or severely damaging the connections. For interior blasts, the pressure wave force walls outward, and floors and roof sections are lifted. The connections rarely survive the loading condition completely intact. Adjacent parts of the structure can also collapse from the loss of vertical and/or lateral support. For blasts initiated outside the building, the near walls may be shattered or blown in, followed by roof sections being lifted, then dropped, and sections of the far side blown out. The failed walls will result in a rubble pile with the interior collapsed floors strewn about.

Heavy Floor Buildings

Concrete framed or shear walled structures usually have heavy floors and walls relative to other structure types. The lift pressures can have devastating effects on concrete slabs in gravity type designs. One-way slabs hinge up because of the lack of top reinforcing at mid-span and lack of continuity splices in bottom bars at supports. The column to beam/slab connection is susceptible to failure when the uplift pressure fails the slab column joint. Once the uplift pressure dissipates, gravity and positive overpressure drives the already damaged slab downward. The “surviving” structure may contain columns that are standing, exposed for several stories without the lateral bracing previously provided by the floors. This occurred in both the 1993 World Trade Center and the 1995 Murrah Federal Building disasters. Large areas of several floors collapsed, leaving columns that extended as far as six stories without lateral support. These columns, still significantly loaded from above, were vulnerable to a sudden collapse and needed to be braced to reduce the risk to rescuers. The collapsed floors create a heavy rubble pile. Unreinforced masonry infills are also susceptible to failure, causing rubble piles and overhead hazards, for concrete frame structures that use them.

Precast Concrete Buildings

In precast frame structures, the lightly (gravity designed) connected floor slabs and wall panels can be readily compromised by the explosive pressures. Like the heavy wall structures, floor to wall connections are critical. However, unlike the heavy wall structures, precast concrete buildings have less structural redundancy and once the connections have been compromised, significant progressive structural collapses can occur. In box-type precast structures, the wall and floor slabs nearest the blast dislodge and brake loose at their joints. The multi-cellular character of these structures (created from closely spaced bearing walls) will, however, tend to limit the collapse damage to those areas where the bearing capacity of wall panels is lost.

Post-tensioned precast concrete structures utilize high strength cables or tendons within the concrete decks to reinforce the structure. If a portion of the post-tensioned cable is damaged, the entire precast floor element will be compromised, which can lead to the collapse of the full length of the precast floor. This type of slab is also very susceptible to upward pressures since the cables are normally draped to lift the weight of the structure. Structural collapse of post-tensioned precast concrete structures often results in a complete pancake area and a partial collapse area between the pancake and remaining structure. A pancake collapse or some sort of draped slab pancake collapse can be formed in the floor structure adjacent to the blast zone. The concrete may also break into small pieces. If the post-tensioned forces have been released, the slabs will act as brittle, un-reinforced concrete. If the post-tensioning forces are still active, great care must be taken if any of the cables need to be cut.

SUMMARY

At a collapsed building incident, emergency personnel conducting search and rescue at the site are focused on locating and extricating victims trapped in the building. The Structures Specialist works within the emergency command structure to minimize risk to the rescue personnel during these rescue operations. The Structures Specialist has the training and background to assess the damage and identify hazards to the rescuers. Evaluating the risk (and considering the reward), the engineer develops a mitigation plan to reduce risk to acceptable levels. This is accomplished with a toolbox of practical mitigation methods that have been standardized and proven through past experience and incidents. These mitigation methods, and the mitigation plan, vary in effort and levels of reduced risk. This paper presents the assessment process, discussing specific building types and incidents, developing a mitigation plan, and the mitigation methods available to the rescue operations.

Expedient Blast Damage and Building Stabilization Assessment

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ABSTRACT

A comprehensive framework for rapid and accurate analysis of buildings damaged by blast loads is outlined. This framework relies on the integration of existing software tools such as: (1) vulnerability assessment software for incident and load definition, (2) an advanced single degree of freedom (SDOF) code for quantifying blast-induced structural damage, and (3) a finite element progressive collapse analysis for global building behavior and stability assessment to identify regions of high risk in the structure. The proposed approach would enable fast responders to quickly assess the condition of a building damaged by blast, in support of evacuation and rescue operations.

1 INTRODUCTION

First responders require advanced computational support tools to assist in building damage assessment for evacuation and rescue operations. Such assessments, if they can be performed fast enough (e.g., from within minutes to a couple of hours) will enable quick life saving decisions. Fast and accurate assessment of buildings subjected to blast loads present unique challenges due to the distinct differences between the behavior of the structure during the blast and post-blast phases. In the blast phase, the structural response is governed by local phenomena that affect individual structural elements, such as beams, columns, slabs and walls that are subjected to the severe short-duration loading environment. The behavior of the structure in the post-blast phase, on the other hand, is global and primarily affected by gravity forces. The structure tries to regain equilibrium by transferring the gravity loads from the structural elements that are lost or heavily damaged to the ones that carry additional loads. If this search for alternate load paths leads to additional local failures, particularly in columns, the overall stability of the building may be lost, resulting in progressive collapse.

The general approach of using a coupled explicit finite element and hydro code analysis for the blast phase, and then using a finite element code to analyze the post-blast response is very intensive computationally and time consuming. Such an approach is not suitable when an urgent assessment is needed by the emergency crews responding to a terrorist event, and the time to model the structure, perform the analysis, and process the results cannot be afforded. An efficient and expedient solution method that can be used to evaluate the extent of damage throughout the structure, determine the risk of progressive collapse, and establish high risk areas is desperately needed (Krauthammer, 2008).

Advanced structural analysis and damage assessment, and expedient progressive collapse capabilities are two of the focus areas at the Center for Infrastructure Protection and Physical Security (CIPPS). These are specifically aimed at both the analysis and assessment of structural behavior during the blast and post-blast loading phases. These research activities are described in the next sections, and they form the basis for a unified expedient and efficient methodology for building stability assessment following blast loading incidents.

2 ADVANCED STRUCTURAL ANALYSIS AND DAMAGE

A variety of approaches, from closed form solutions for simple cases to high-fidelity finite element solutions for more involved problems, have been employed for the analysis of structural components under impulsive loads. At CIPPS, one of the key research areas has been the development of an efficient and easy to use computational tool for expedient, yet accurate, numerical support of both design and assessment of structural systems subjected to severe dynamic loads. The Dynamic Structural Analysis Suite (DSAS) was initially introduced in the early 1980s, and it has been under continuous development since. The latest version, DSAS 2.0, has grown considerably in terms of features and capabilities and is fully compatible with the latest operating systems and processor technologies (Astarlioglu and Krauthammer, 2009). Yet, it can run in computers with modest specifications, while ensuring the installation and execution on the most recent Windows operating systems.

The primary analysis engine in DSAS is based on an advanced single degree of freedom (SDOF) formulation that is capable of performing fully nonlinear time history analyses of a wide range of structural steel or concrete components (e.g., beams, columns, walls and roof slabs, and buried boxes). The program does not rely on simplistic elastic-perfectly plastic resistance functions, but employs a sophisticated displacement-controlled solution algorithm for obtaining the resistance function for beams, columns, slabs, and walls. For slabs, walls and boxes, the resistance function is derived using advanced compression and tension membrane approaches. DSAS also checks for failure in the direct shear mode of response in addition to combined flexure-diagonal shear-axial force responses in other reinforced concrete components. For reinforced concrete, steel, and masonry members, DSAS evaluates the load and mass factors as a function of displacement rather than constant values for elastic, elastic-plastic, and plastic ranges. Figures 2 – 3 show the resistance function, load factors, and mass factors of a simply supported steel beam determined by DSAS, respectively

DSAS can rapidly assess whether a component will fail or survive a specific threat (either from a conventional, or nuclear explosion), and how much damage will occur given the geometric and material properties of the component. In addition to running analyses for a single threat, DSAS can also run in a Pressure-Impulse (P-I) mode to assess the range of threats that will cause the structure to either fail or sustain a specific level of damage. One can develop a family of P-I curves for pressure and impulse combinations that will cause yielding, specified value of support rotation, specific deflection or strain level, or total failure. Furthermore, for columns, DSAS can be used to plot P-I curves for different axial load levels. Figure 5 shows the P-I curves of a reinforced concrete column subjected to blast loads for varying levels of axial load.

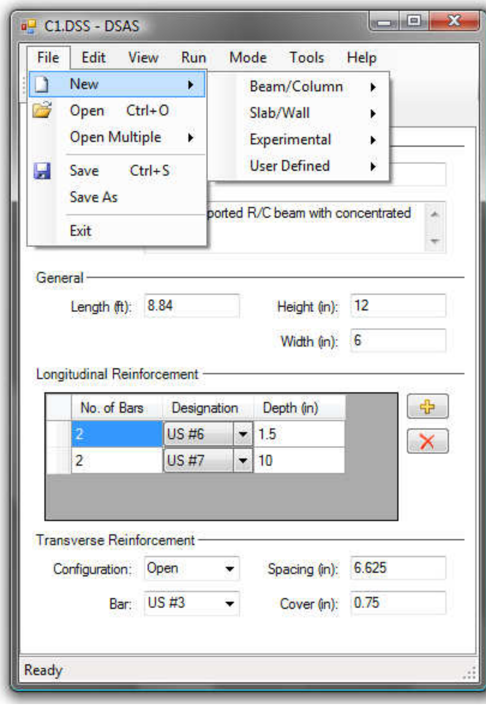


Figure 1: DSAS user interface

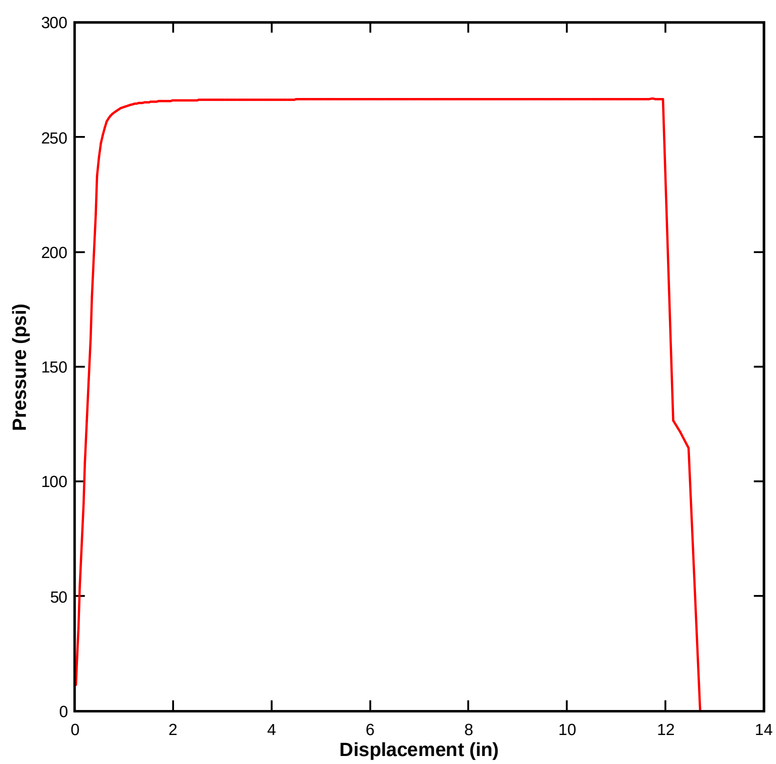


Figure 2: Resistance curve of a simply supported steel beam under uniform load

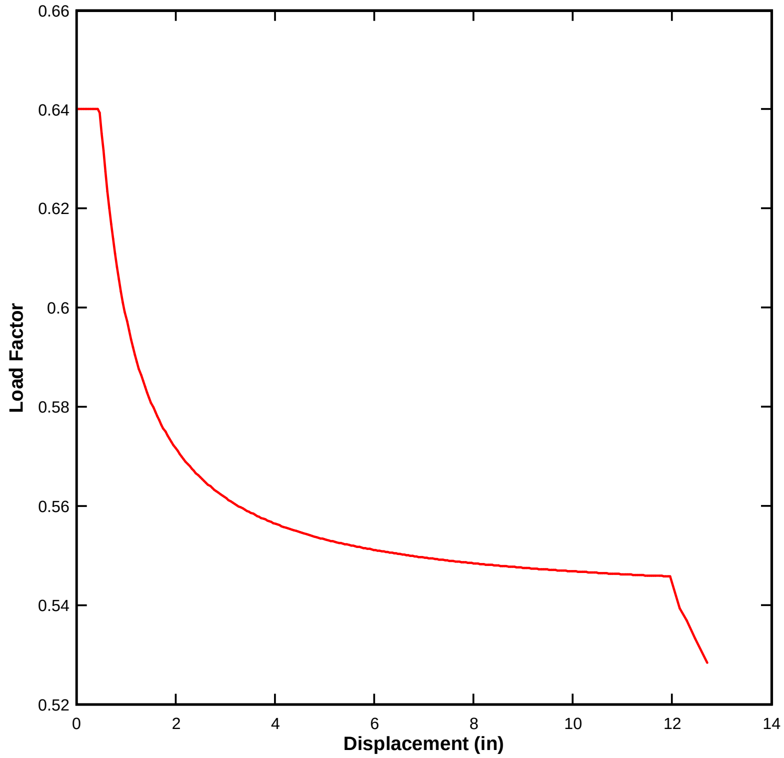


Figure 3: Load factor curve of a simply supported steel beam under uniform load

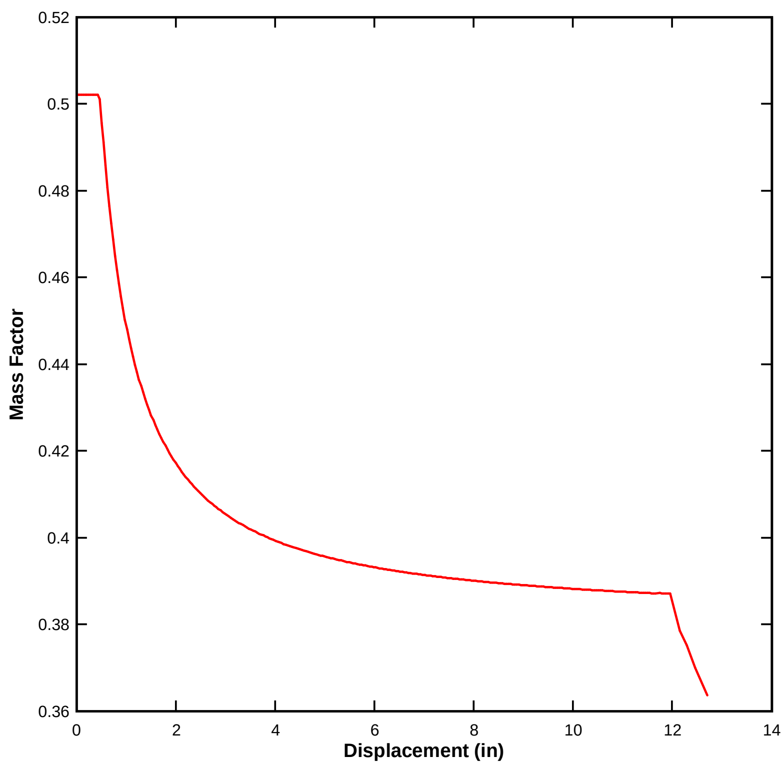


Figure 4: Mass factor curve of a simply supported steel beam under uniform load

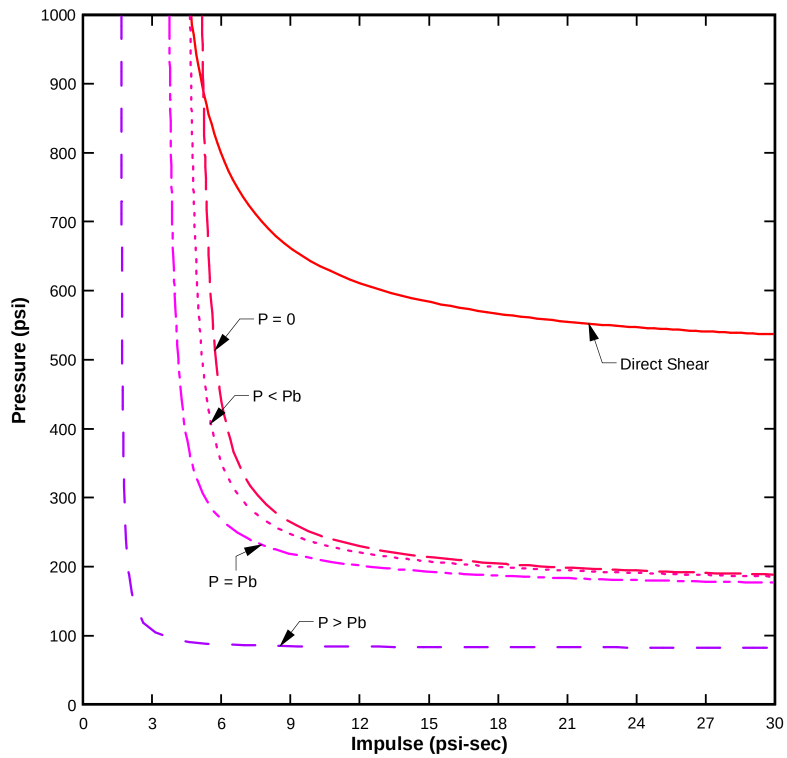


Figure 5: PI curve of a reinforced concrete column with different levels of axial load

2.1 Capabilities and Features of DSAS

The component library in DSAS 2.0 contains the following components:

- Reinforced concrete beams and columns with rectangular cross sections,
- Reinforced concrete columns with round cross sections,
- Reinforced concrete standard joists,
- Steel beams and columns with wide flange cross sections,
- Steel beams with channel cross sections,
- Steel beam and columns with tube cross sections,
- Masonry block walls,
- Masonry brick walls,
- Reinforced concrete slabs,
- Reinforced concrete buried boxes,
- Wood panels,
- Simple and advanced user defined components.

2.2 Reinforced Concrete Components

The user can provide the input rapidly by simply providing the section dimensions in U.S. customary and metric reinforcing bar tables. For rectangular sections, any number of layers or reinforcement can be specified. Both confined and unconfined concrete models are available, and the amount of confinement is automatically determined based on the type and amount of confining steel. For the longitudinal reinforcement, the user can select between elastic-perfectly plastic and strain hardening steel models. For columns, the gravity load on the column can be included in the analysis. For buried boxes, the resistance function considers in-plane compressive force due to internal membrane effect and external thrust due to wave propagation in the backfill. The output includes moment-curvature diagrams (beams and columns only), resistance functions, and the time history analysis results for both the flexural (combined with diagonal shear and thrust) and direct shear degrees of freedom.

2.3 Steel Components

The user can either select the sections from the built-in AISC database or define a custom built-up section. Loads can be applied either in the strong axis or weak axis directions, and the effects of local buckling are also included in the derivation of the resistance function. The material model for the steel can be selected as elastic-perfectly plastic or strain hardening. For columns, the gravity load on the column can be included in the analysis. The output includes moment-curvature diagrams, resistance curve, and the time history analysis.

2.4 Masonry Components

The user can analyze ungrouted, partially grouted, and fully grouted CMU walls with or without reinforcement using the masonry block wall module. Single-Wythe or two-Wythe (with or without grout and reinforcement) brick walls can be analyzed using the masonry brick module. The axial loads from the supported slabs can be included in the analysis as additional axial loads. The output includes moment-curvature diagrams, resistance curves, and the time history analysis.

2.5 Wood Panels

Unlike the resistance functions of the previous components which are numerically derived, the resistance functions for the wood panels are based on experimental data obtained from testing of 48” x 96” panels with 2x6 studs at 16” on center and 0.5” thick plywood sheet. The available connection types are: stud to sheathing, stud to plate, and plate to floor. The user can select the connection type and whether adhesives are used or not. The output includes the resistance curves and the time history analysis.

2.6 User-Defined Components

For these types of components, the user is required to provide the resistance function as a data table. If the mass and load factors are constant throughout the analysis, and only a nonlinear displacement-resistance curve is provided, the simple user defined component can be used. For cases where the load and mass factors are also a function of the displacement, the advanced user defined component can be used. These components are suitable for cases ranging from simple mass damper analysis to cases where the user has the resistance function obtained experimentally or analytically and is interested in performing time history analysis or plotting pressure-impulse diagrams.

2.7 Loading Functions

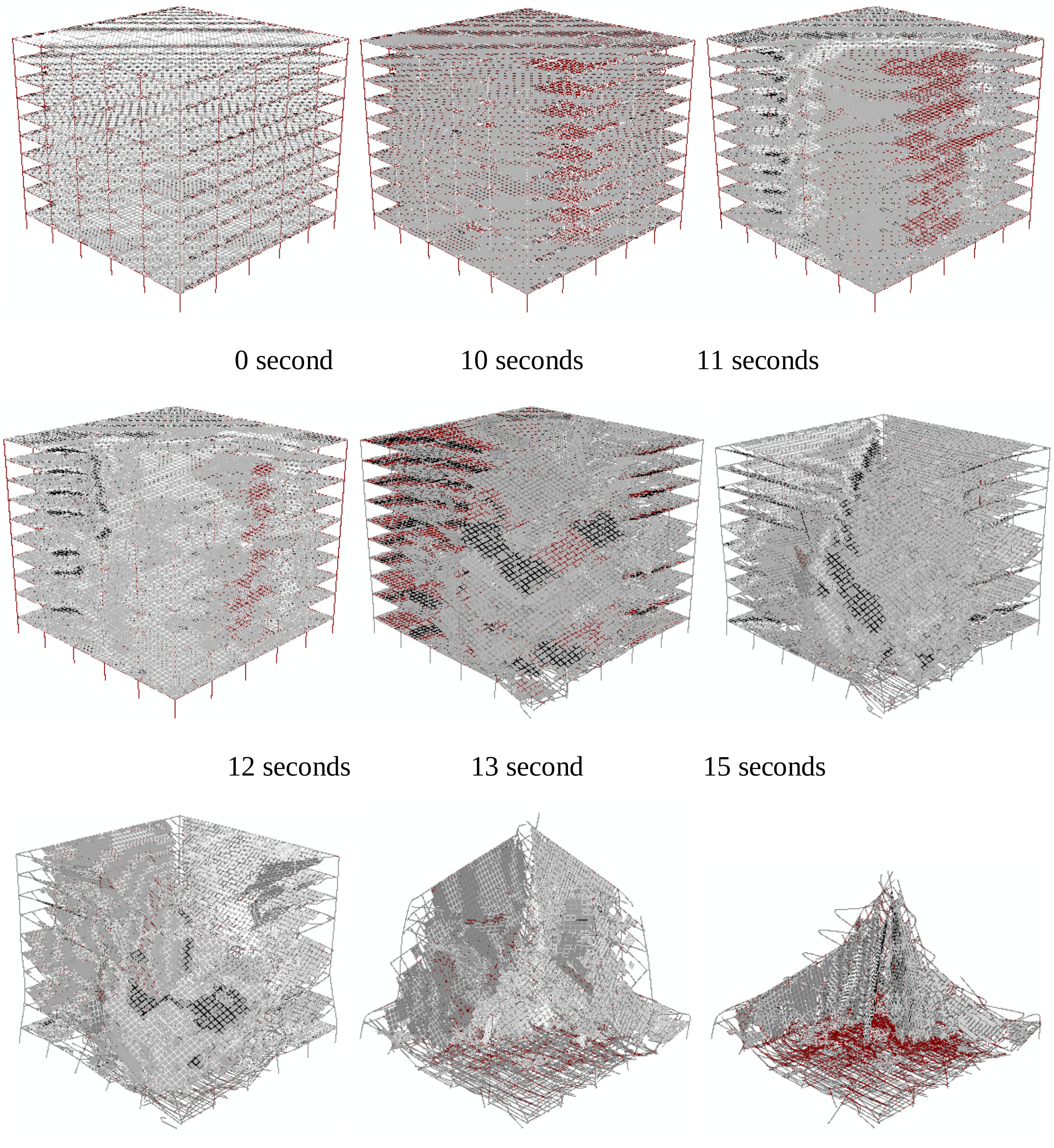
DSAS offers several different loading options based on the component type. Point loads (beams and columns only) or uniformly distributed loads can be specified and force vs. time or pressure vs. time values should be provided, respectively. If the air blast option is selected, the charge weight (or yield for nuclear devices) and the location of the charge relative to the component should be provided. DSAS internally generates the pressure-time history on the component by meshing the target surface into small elements and averaging the pressure-time histories on each element. Additionally, pressure-time histories can be imported from ConWep and BlastX output files. For buried boxes, DSAS can generate the surface pressure-time history from the charge weight (or yield for a nuclear device), range, and height of burst. The surface pressure is then propagated through the geologic media, as an airblast-induced ground shock, to define the pressure-time history on the loaded surfaces. If the charge is also buried, DSAS can compute the direct-induced ground shock to define the pressure-time history on the loaded surfaces.

3 POST-BLAST PROGRESSIVE COLLAPSE ANALYSIS

After a blast event, frame and connection analyses of a building are conducted based on the local damage information for each structural element. The progressive collapse assessment is achieved through numerical simulations of building layouts and selected loading scenarios. The analysis enables one to study the observed behavior, compile a response database, and identify the global and local behaviors. The connection properties for various connection types are characterized by mechanical models that were extracted from quasi-static analyses whose results have been implemented in extensive data bases. Dynamic explicit finite element analyses are used to diagnose the total building performance under sudden column removal scenarios (e.g. single corner column removal, single corner and an external column removal, single corner and an internal column removal, two external column removals, etc).

3.1 Frame Analysis

Figure 6 illustrates the frame analysis results for a 10-story building with ABAQUS (Dassault Systems, 2008) when one corner and two exterior columns are removed. The first failure behavior was shown at the adjacent internal columns. As the connections around the initially removed columns failed, the adjacent columns became unstable, and, as a result, the floors above the removed columns started to fail. The governing structural behavioral mechanisms of building frames can be identified based on results from the finite element simulations that can identify load paths and corresponding structural member behavior or damage (e.g., column buckling, beam plastic hinge, or connection failure). The damage examination starts from an initiation point and attempts to propagate through members connected to it. Tracking is conducted in both the vertical (to members on adjacent floors) and horizontal directions (within the floor of a responding structural). If plastic hinges or connection failures occur, the load flows will be redirected through intact members that can transfer the force flows. The damage propagation will be arrested if the transferred loads are resisted by the surviving members. However, excessive local loads could cause additional local failures (e.g., member or connection failures, dynamic column buckling, etc.). Realistic load or energy propagation could be used to evaluate high-rise building behavior without the use of expensive and time-consuming simulation models.



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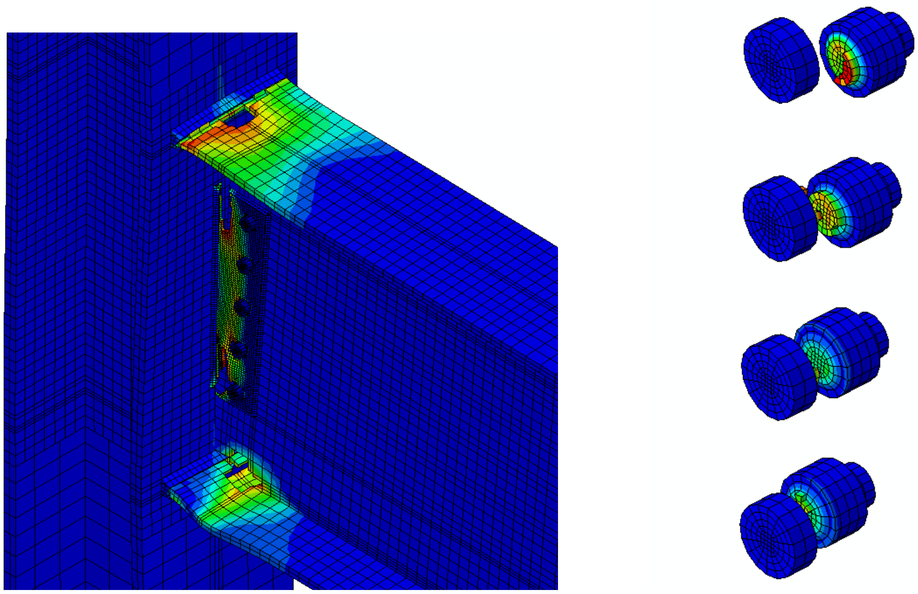
12 seconds 13 second 15 seconds

16 seconds 17 seconds 20 seconds

Figure 6: Progressive collapse analyses (10-story building)

3.2 Connection Analysis

Our research has shown the importance of beam-to-column connections, where the connection properties and behavior influence the frame stability and possible progressive collapse outcomes. For relatively small local failures, strong connections enable bridging the loads to undamaged structural regions. However, in the case of severe local damage, such as bridging over damaged zones, may not be attained. Also, previous research concluded that the frame rigidity would be overestimated when the frame contains idealized connections (fully-rigid moment connections) instead of realistic semi-rigid connections as shown in Figure 7. Idealized connections could not represent the frame instability in terms of impairment of force transfer functions or beams-column separation. This phenomenon is more obvious in taller buildings, due to heavier tributary forces distributions adjacent to the initial local damage area. Therefore, the connection properties should be defined accurately and in sufficient detail to insure more reliable progressive collapse predictions. Such connection details would inevitably lead to prohibitive computational resource requirements, and they are the main cause for developing simplified structural models. However, unreliable results are obtained if such simplified models do not accurately represent the physical behaviors of all structural components. Consequently, mathematical-mechanical models have been extracted from fully nonlinear 3D analyses that capture accurately the behavior of different types of connections, as shown in Figure 8. The structural components are then assembled into a building model that can represent appropriate connection properties and overall structural behavior.



(a) weld failure of moment connection **(b) bolt failure of shear connection**

Figure 7: Realistic connection behaviors

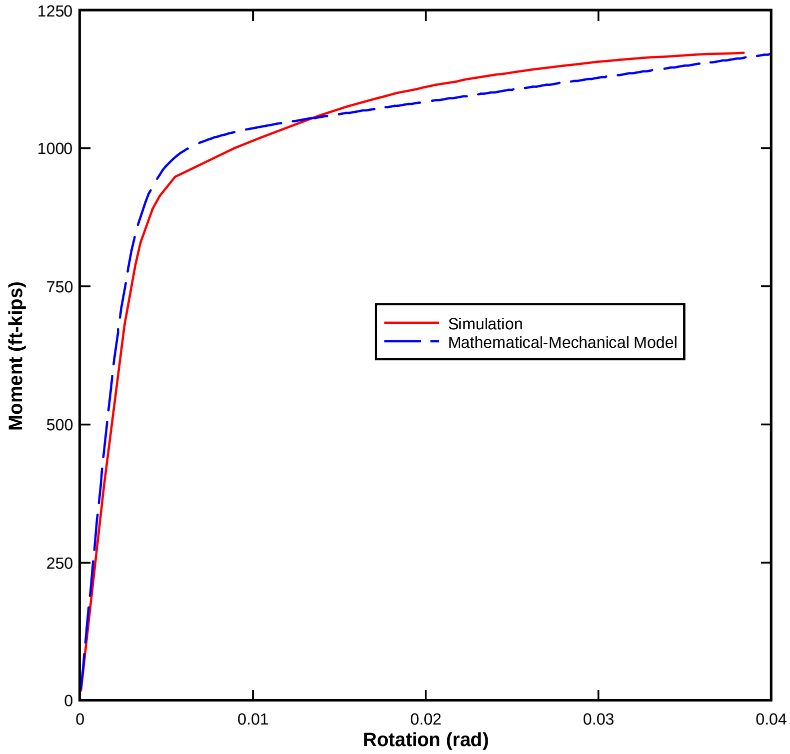


Figure 8: Moment-rotation relationships from simulation results and mathematical-mechanical model

4 A UNIFIED APPROACH

While DSAS can be used to assess the damage sustained by individual structural members from given loads and their connector models, as described in the previous sections, to enable the subsequent structural stability analysis to be performed in a reasonable amount of time. A vulnerability assessment tool, such as ATPlanner, has been adopted and will be modified for defining the loads that are applied to each structural member.

ATPlanner (ERDC, 2007) is a software tool for predicting structural damage and blast zones surrounding an improvised explosive device (IED) attack. User provided information about the size, type, and distance of the IED, structural characteristics including geometric and material properties are used to set up a specific case. However, the current version of ATPlanner has limitations that must be addressed prior to adopting it for use with DSAS, and fast running progressive collapse analysis. These include: the floor plans are limited to rectangular layouts, the floor-to-floor height is constant throughout the building, and assigning different column sizes to different bays is not allowed. Furthermore, the damage determination is done using pressure-impulse diagrams that are derived empirically. The DSAS enhancements to ATPlanner will add robust and accurate structural response prediction capabilities, as well as the derivation of Physics based pressure-impulse (P-I) diagrams.

The accuracy and the reliability of ATPlanner will be greatly enhanced by utilizing DSAS as the computational engine for performing structural response and P-I analyses. Furthermore, ATPlanner will be modified to serve as a bridge with subsequent building stability analysis by exporting the load information to DSAS and importing the damaged state back. Subsequently, the damage will be mapped into the finite element mesh of the building for collapse analysis. This approach, shown in Figure 9, will not only speed up the analysis time significantly, but also lead to a more realistic analysis approach than currently available.

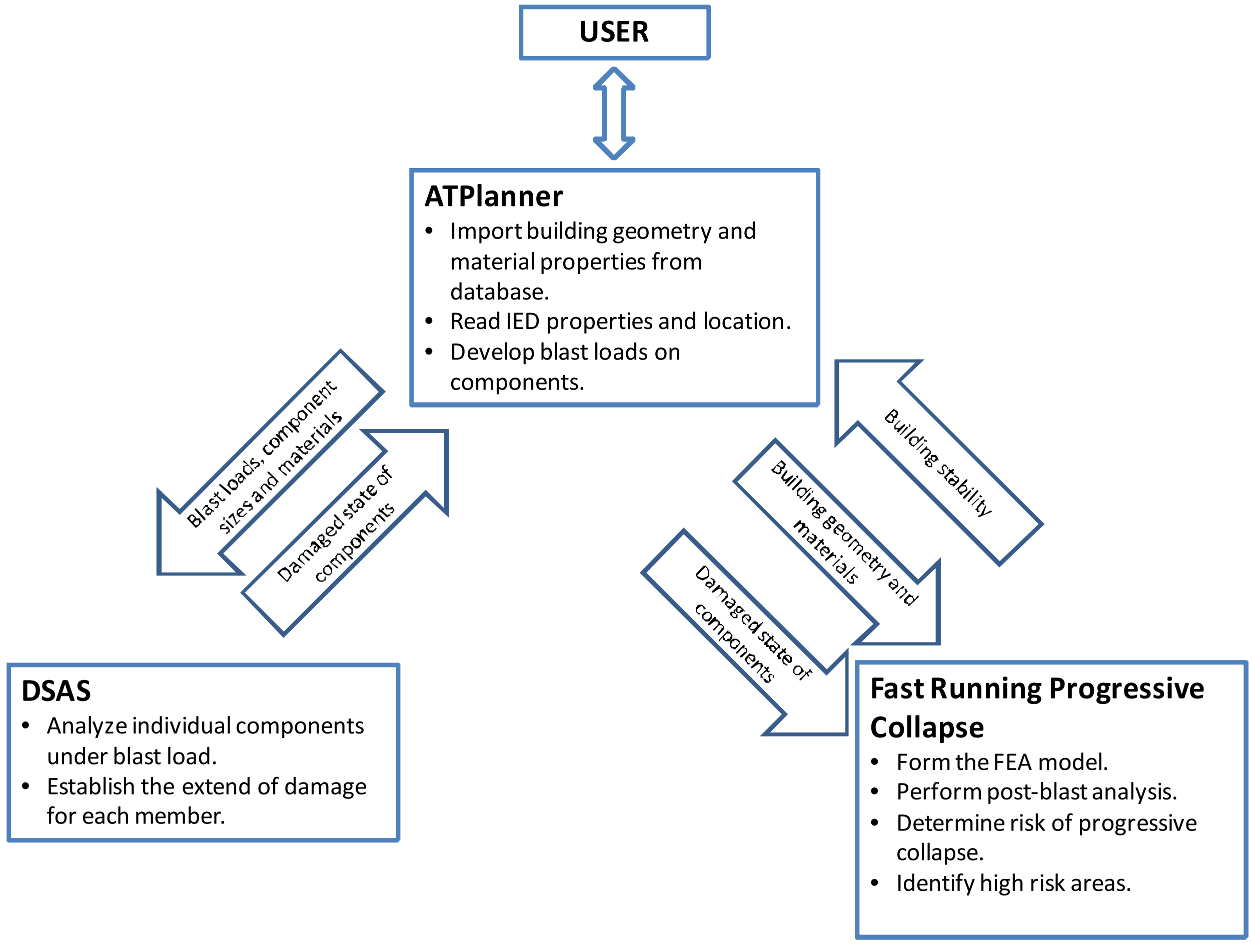


Figure 9: Framework for fast building risk assessment

Since obtaining the information related to building floor plans, construction materials, etc, may not be readily available when needed right after an attack, it is also prudent to develop a database of buildings that are at high risk of being the target of an IED attack in support of this assessment framework. Furthermore, this approach can be enhanced further by incorporating an artificial intelligence (AI) user interface that can guide the operator in expedient blast damage assessment (e.g., Krauthammer et al. 1992), and performing the subsequent correct building stability assessments and related operations in the most effective sequence.

5 ACKNOWLEDGEMENT

The authors acknowledge the support and cooperation provided by the US Army Research and Development Center (ERDC) and by the General Services Administration (GSA) for this effort.

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Monitoring Stability Loss in Burning Buildings

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Keywords: Fire-induced vibrations, stability indicators, impending collapse

ABSTRACT

Structural health monitoring has been largely promoted as a means for assessing the condition of buildings and other critical structures in the aftermath of significant events. Support for installation of real-time monitoring devices and systems, however, continues to lag due in part to the absence of clear and convincing benefits to owners and to the structures themselves. A case can be made that a fresh approach, or application, may be needed to bolster the case for real-time structural health monitoring.

Firefighting operations and the accompanying risks are typically scrutinized and reviewed anytime loss of life results. In recent history, no single event has drawn more attention to the technology and methodology of modern firefighting technique than has the collapse of the World Trade Center Towers. The collapse of those structures and the corresponding loss of life reveled vulnerability in the absence of real-time health monitoring that may have informed firefighters of the weakening structural conditions around them.

Under a previous research effort funded by the Building and Fire Research Laboratory and the National Institute of Standards of Technology (BFRL/NIST), a new methodology that employs fire-induced vibration monitoring to track stability loss was first demonstrated in tests conducted on a single-family wood frame structure in Kinston, North Carolina (August 2001). In those tests, a heating oil tank was mounted on the roof of the structure in an effort to induce roof collapse during burn. The objective of that test was to evaluate the possibility of measuring fire-induced vibrations in a burning structure that correlated with weakening conditions leading to a significant collapse event. Those tests demonstrated for the first time, that fire was capable of exciting dynamic structural vibration responses that provided real-time indication of impending collapse. Figure 1 shows a picture of the building on fire with a 250 gal heating oil tank mounted on the roof (top) and a sample of fire-induced responses (bottom) acquired during the test. A practical implementation of the technique requires a reliable stability indicator that can be used to supplement information typically available to firefighters during operations. For example, during burn tests on a large wooden frame building, stability indicators based on measured fire-induced responses tracked the impending collapse of a cantilevered overhang, as shown in Figure 2.

A description of the theoretical background for the approach, of the fire-sensor and application, and of the interpretation of fire-induced response behavior is presented. Sample results from full-scale burn tests on actual buildings, and the implication for tracking weakening conditions in large buildings are also discussed.

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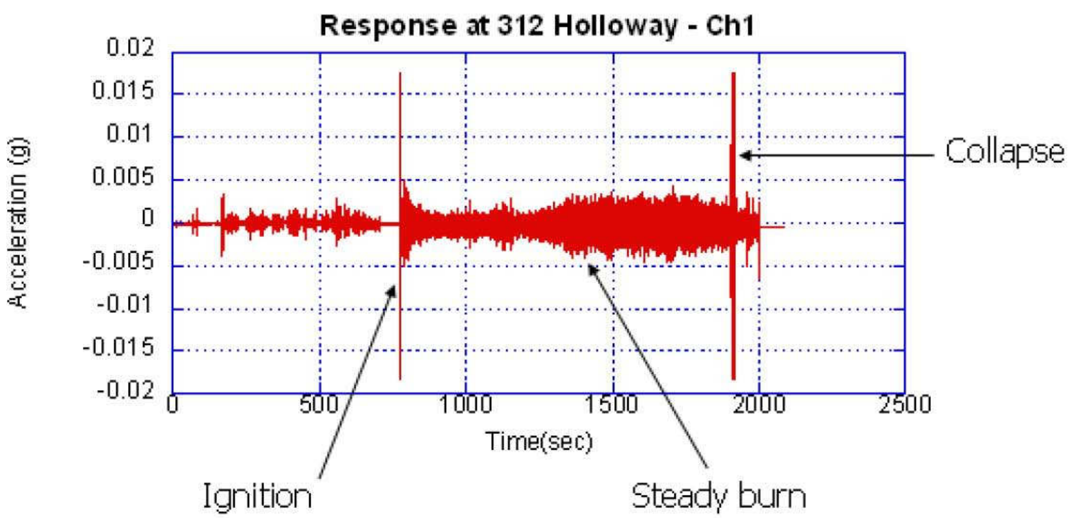

Figure 1: Fire-induced monitoring of a wood frame structure

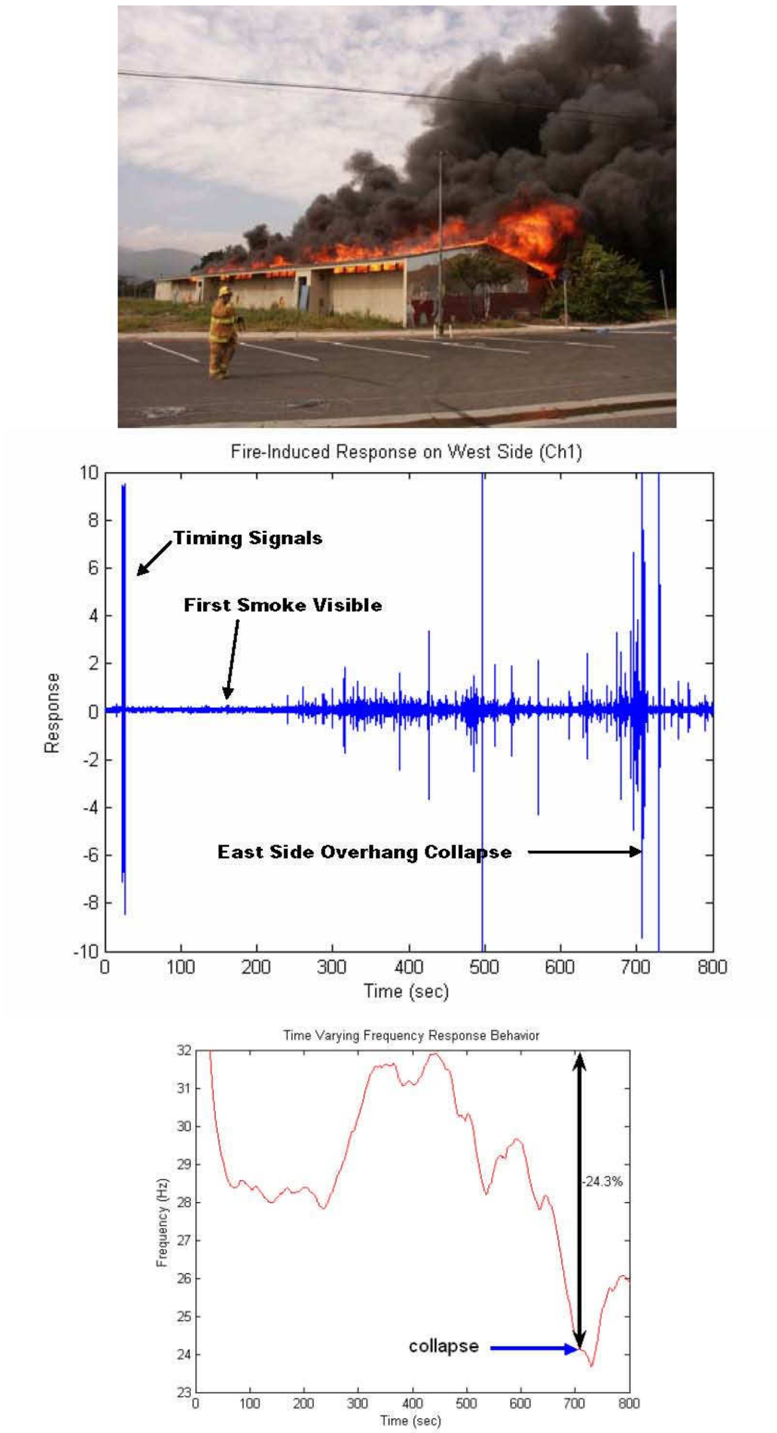

Figure 2: Burn tests on a large wooden frame building (top), measured fire-induced response (middle), and stability indicator (bottom).

Structures Subjected to Blast Loading: Protection, Stabilization and Repair

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To rise to the challenge of protecting the nation against the attack of terrorism, in the form of physical, chemical, and biological weapons, targeting transportation, energy, infrastructure, information, and health care systems, researchers at the University of Mississippi formed an interdisciplinary research group Nano Infrastructure Research Group. The main focus of the group is on using advanced materials (e.g., nano materials) and computational tools to help protect the nation against the threat of catastrophic terrorism. The group goal is to move the utilization of nano materials from high performance applications with labor-intensive processing to high performance, low cost, and energy efficient technology suitable for application in infrastructure sectors. The group has joined forces with national labs (National Institute of Standards and Technology and U.S. Army Engineering Research and Development Center), industrial partners, and several universities. One of the group's current research projects focuses on using nano structural or structural retrofitting materials for critical infrastructure protection. The final report of phase I of the project may be found online at http://www.olemiss.edu/sciencenet/ftp/DHS%20nano%20final%20report.pdf. The research takes the multi-pronged and integrated approach, simultaneously addressing four research areas:

- Material Research: New materials ranging from carbon nanotube, xGnP (exfoliated graphene nanoparticle), POSS (polyhedral oligomeric silsesquioxane), and nano clay-reinforced polymers and concrete.
- Structural Component Research: Innovative structural components and subsystems ranging from grid and foam stiffened panels and tubes to elastomer-coated walls.
- Structural System Research: The dynamic response and damage of small and large buildings and structures exposed to blast/impact (e.g., terrorist act, accidental explosion) and severe natural (e.g., tornado, hurricane, earthquake, fire) hazards.
- Decision Support System Research: Tools to generate different threat scenarios, for defining defense and protection barriers, for recommending retrofitting measures, and for evacuation planning.

Main findings of the project are summarized below:

MATERIAL RESEARCH

1. Molecular Dynamics Simulation: Theoretical material database has been constructed for nanoparticle reinforced composites and other low-cost, high-strength, innovative materials, based on Molecular Dynamics (MD) simulation. The materials investigated include: (i) SWCNT (single-wall carbon nanotube)-polyethylene, MWCNT (multi-wall carbon nanotube)-Nylon 6, XGnP (exfoliated graphite nano platelets)-vinyl ester, montmorillonite clay-vinyl ester nano composites, for a range of volume fractions; (ii)

Low cost polymer matrices: Nylon-6 thermoplastics, polyethylene thermoplastic and vinyl ester thermosets; (iii) Crystalline constituents of hydrated cements, including alite (C3S), belite (C2S), aluminite (C3A) and brownmillerite (C4AF); and (iv) Rock minerals: quartz, calcite, dolomite, feldspars, and mica.

2. Nano Indentation: Nano indentation is being used to obtain local properties of nano composites.

3. Dynamic Mechanical Analysis: Experimental database, which includes modulus (stiffness) and damping (energy dissipation) properties of materials, has been constructed for nano-particle reinforced composites, MWCNT-nylon 6, clay- vinyl ester, and XGnP-vinyl ester, using DMA.

4. Particle Dynamics (PD): PD computer code was developed to bridge the modeling gap between the nano to micro scales, and used for the study of air blast, ballistic and debris impact, and thermally induced fractures.

Structural Component Research

5. Reinforced Concrete (RC) Columns: A procedure for computing pressure impulse (P-I) curves has been developed using SAP2000 and Matlab software which is consistent with TM 5-1300 methodology. A database of curves has been created for reinforced concrete column sizes and reinforcement ratios representative of low-rise buildings in Mississippi satisfying 2006 IBC provisions. A damage mapping procedure has been developed to characterize slight, moderate, and severe damage levels on exterior framing of a building face exposed to blast loading for various charge weight and standoff distance.

6. Concrete Masonry Unit (CMU) Infill Walls: The effect of the blast loading onto CMU infill (non-load bearing) wall panels with and without retrofit was evaluated using AUTODYN software. Repair materials evaluated include: polyurethane, polyurea, E glass FRP, S glass FRP, XGnP-nylon 6 nanocomposite, XGnP-polyurethane nanocomposites, XGnP-Polyurea nanocomposite, siloxane nano-coating. A database of P-I curves, maximum displacement, debris velocity, midpoint velocity, energy absorbed and reaction forces was generated.

7. Structural Sandwich Panels: E-glass sandwich composites with foam cores subjected to high energy blast loads are being investigated using finite element analysis for optimal design configurations.

8. Shock Tube Testing: Nano composite panels were experimentally studied for blast resistance in a controlled shock tube experimental facility. Database has been constructed.

9. 1/3 Scale Blast Load Simulation (BLS): The BLS facilities at ERDC were used to evaluate blast response of 3’ x 4’ 1/3 scale CMU and 4’ x 4’ full-scale sandwich composite panels (both with and without elastomeric nano-coatings or nano films) to blast pressure waveforms of up to 20,000 lbs explosive yields and peak reflected pressures up to 80 psi, simulating blast loads from terrorist bombs.

10. Low Velocity Debris Impact: DYNATUP Model 8250 instrumented impact machine was used to evaluate the energy absorption of nano composites subjected to low velocity impact.
11. Intermediate Velocity Debris Impact: Split Hopkinson pressure bar experiments were conducted for stress-strain characteristics, failure strength, and energy absorption of nano-composites.
12. High Velocity (Ballistic) Impact: Ballistic testing of nano-composites is being conducted using gas guns at firing range for both sequential and simultaneous impacts with three projectiles.

Structural System Research

13. Simulation of Building Progressive Collapse: A typical 3-story RC building subjected to blast load is investigated using SAP2000 nonlinear static and dynamic finite element analyses for the progressive collapse scenario. The energy absorption characteristics of the floor and roof systems, and the influence of column spacing have been investigated.
14. Field Investigation: A full scale 2-story RC building collapse under 1st floor column removal of an end frame was videotaped during a field demolition activity. Deformations and vibration response were measured at each stage of removal up to removal of all three columns in the end frame. The collapse sequence has been simulated using a SAP2000 model.
15. Fully 3-D Dynamic Simulation of Building Subject to Blast: A high-fidelity LS-Dyna model has been developed for a 3-story building representing a characteristic RC building structure (2 x 3 bays, 20 x 40 ft column spacing, members sized to satisfy 2006 IBC provisions). The dynamic pressure loading has been developed using the CONWEP procedure in LS-Dyna and the nonlinear dynamic response of un-retrofitted and retrofitted structures have been computed.

Decision Support System Research

16. Blast Protection Barrier Planning: The Sillers Building in Jackson, Mississippi (the State's Executive Building housing the Governor and the Attorney General's offices) was investigated for blast and protection barrier planning. Car bombs were set off at different standoff distances created by protection barrier, and building damage was assessed with and without wall structure retrofitting.
17. Emergency Evacuation Planning: E-Sim software is used to simulate the evacuation scenarios of the Sillers Building for the various blast and building retrofitting scenarios. The software has the following capabilities: (1) model the movement of humans during normal or emergency situations; (2) serve as an assessment/diagnostic tool to determine optimal ingress/egress solutions for facilities, (3) examine where bottlenecks or problems exist, (4) evaluate and develop emergency plans, (5) aid in the design of ingress or shelter-in-place for new facilities and major renovations, and (6) assist in training and planning simulations.

18. Mississippi Critical Infrastructure Database: An inventory of state-owned facilities has been obtained from the Mississippi Emergency Management Agency (FEMA). This inventory supplements the one which was developed of critical facilities in north Mississippi by a field survey performed as part of a Mississippi Emergency Management Agency (MEMA)-sponsored HAZUS-MH earthquake modeling study by the University of Mississippi's Center for Community Earthquake Preparedness.

Detailed discussions of two levels of evaluation that are more related to the objectives of this workshop are summarized below (see Cheng et al., 2009).

1 STRUCTURAL SYSTEM RESEARCH

1.1 Fully 3-D Dynamic Simulation of Building Subject to Blast

The objective of the Structural System level of research is to examine the potential benefits of using nano particle reinforced composites to enhance structural components in a full scale critical infrastructure system. The application selected in this study is a reinforced concrete (RC) moment resisting frame (MRF) structure commonly found in many hospitals, schools, emergency operations centers, and federal office buildings throughout Mississippi and other states. To obtain a basic understanding of the complex behavior of such systems under the extreme dynamic loading developed during blast events, a representative structure of relatively simple configuration shown in Figure 1 was analyzed.

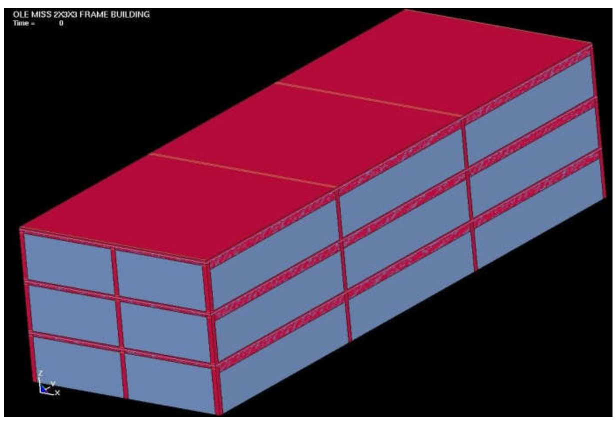
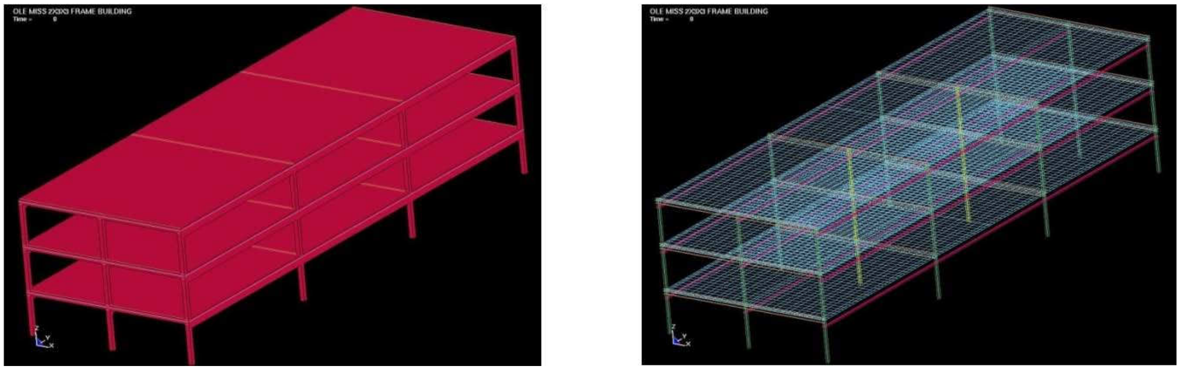


Figure 1: Representative RC MRF critical facility including curtain walls

Design of the representative RC frame structure components was first performed assuming the building was adequate under all basic loads and load combinations called for in national building codes. For this study, the 2006 International Building Code was assumed to have been adopted by the building authority at the site of construction of the representative critical facility. This approach avoids the distinction between design of a new facility and retrofit of a recently constructed one in which blast resistance has not been considered.

The results of the designs were provided to the finite element analyst, Dr. James O'Daniel, ERDC Blast and Survivability Group, Vicksburg, MS. Dr. O'Daniel used the gross sections and steel reinforcement sizes and spacing to develop the overall LS-Dyna model shown in Figure 1 which has been Figure 2 shows the finite elements model corresponding to the concrete frame and steel reinforcement systems, respectively.



a. Concrete frame and slab subsystem (~300,000 solid elements)

b. Steel reinforcement elements (~56,000 beam elements)

Figure 2: Representative RC MRF critical facility including curtain walls

Bay spacing was L ft in the transverse direction and 2L ft in the longitudinal direction and each story height was 12 ft. All column gross sections were square with perimeter columns 12 in. wide and interior columns 16 in. wide. All beam gross sections were rectangular with transverse beams 6.5 in. x 13.0 in. and longitudinal beams 13.0 in. x 25.9 in.

Use of nano particle reinforced wall panel protection was taken to be the primary consideration in the absence of specific vulnerability information of RC MRF to blast threats. To characterize the behavior of the full size curtain wall panels, a series of LS-Dyna simulations was performed to establish load deformation patterns consistent with the reduced scale blast simulator tests and a range of expected blast and response conditions of actual buildings.

Shell elements with equivalent elastoplastic material representing retrofitted walls were used assuming the nano particle reinforcement was fully effective. Three different equivalent strength levels were considered representing single, double, and quadruple levels of the wall yield strength. Two sets of boundary conditions were considered representing complete fixity on all four sides and one case in which the bottom edge was free or not tied to the supporting floor or foundation. These cases transmit significant load to the primary structure. Figure 3 shows characteristic pressure-displacement curves and a snap-shot of one of the panel simulations.

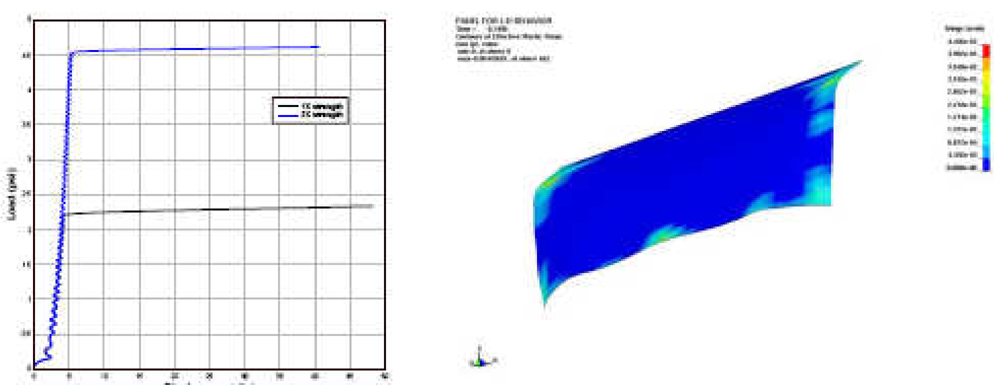


Figure 3: Pressure displacement and effective plastic strain distribution for wall panel

The representative building model in Figure 1 includes approximately 43,000 of the curtain wall shell elements. Two external blast locations were considered corresponding to an end wall exposure and an offset side wall exposure. Charge weight and distance were varied to examine local and global damage effects. Examples of results of the eccentric side blast scenario are shown in Figure 4 for the three blast charge weights.

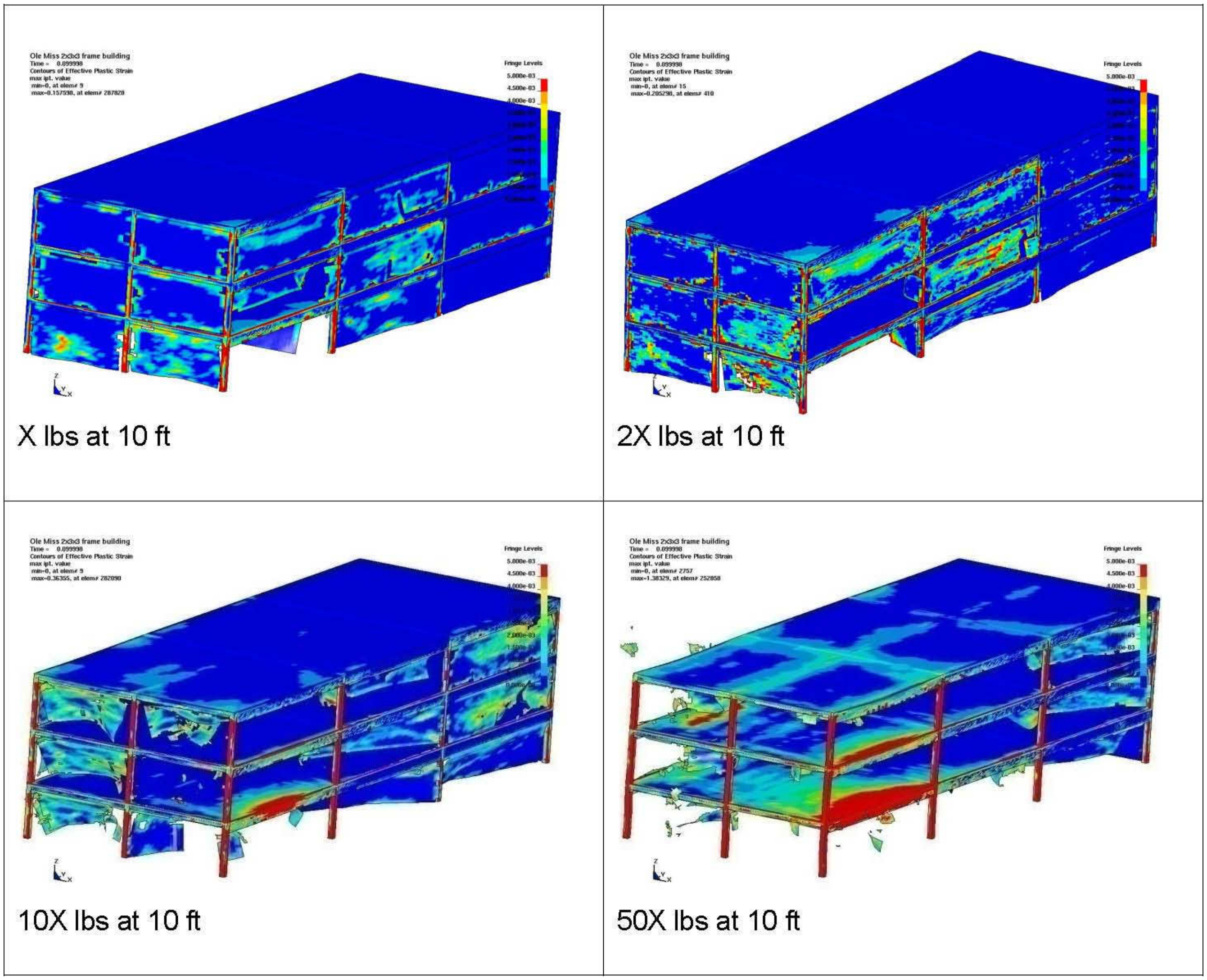


Figure 4: Effective plastic strain distribution for eccentric side blast scenario

1.2 Full Scale Tests of RC MRF Subsystem Collapse

Demolition of graduate student housing on the campus of the University of Mississippi enabled opportunistic full scale field tests of three nearly identical two story RC MRF structures in December of 2007. The structures were built in the late 1950's and consisted of multifamily apartment units with common access via interior stair wells. Each building was designed as an RC MRF structure with cast-in-place RC floor and roof slabs poured and reinforced compositely with the frame elements. The exterior perimeter frames were constructed with brick infill walls. Bathroom areas and slab openings created by stairs were stiffened by RC shear walls.

Construction drawings obtained from the University Physical Plant indicate that the structures were designed for lateral wind loads but building codes in the region had not yet adopted seismic provisions. Codes at the time required only a 75 mph nominal wind pressure whereas 2006 IBC now calls for a 90 mph 3 s peak gust load.

Working with the demolition contractor, a series of column removal sequences (Figure 5) was performed to imitate two of the basic scenarios called for in the GSA guidelines (GSA, 2003) applicable to design of U. S. government buildings. The GSA guidelines were developed primarily under contract to our partner in this project, Applied Research Associates, Inc., (ARA) located in Vicksburg (see Decision Support Level). The guidelines are primarily aimed at preventing the type of progressive collapse that occurred following the 1995 bombing of the Alfred P. Murray Federal Building in Oklahoma City.

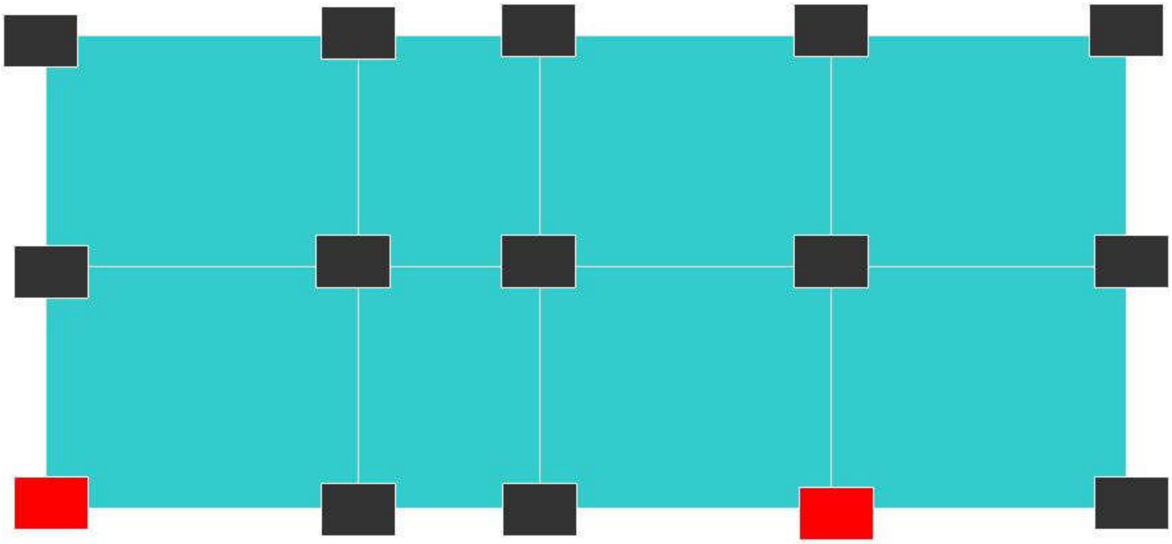
Emulating the first GSA scenario, a corner column was removed. The deflections of the structure were measured using a Total Station set up at about 86 ft due to safety considerations. Immediately after the removal of the corner column (about 5 minutes), the relative deflection of the slab at the corner was measured. The corner was found to be displaced downward by 0.013 ft. (0.156 inch). No cracks which could be attributed to the column removal were detected in the beams or beam column joints. Further damage was achieved by impacting the slab with the head of the shearing machine. About fifteen impacts from the 3000 lb shearing head from a height of 2-3 ft were necessary to cause the complete collapse of the slab. This provides a qualitative measure of the reserve capacity in the structure.

The failure sequence was as follows: 1) Prying out of top column rebar from the slab. This was due to damage caused at the column joint due to earlier removal of the ground floor column. 2) Increased deflection in the slab no longer supported at the corner and formation of hinges near supports in beams on both the exterior sides of the slab. 3) A yield line was formed in the slab leading to collapse which is consistent with that expected by theory.

For the second GSA scenario an interior perimeter column was removed. Prior to removal of the column, the unreinforced CMU infill wall behind the column was removed. Immediately after the removal of the column, a downward deflection of 0.020 ft (0.24 inch) was measured at the position of the removed column.

Overall the structure was found to have significant reserve capacity due to over designed members. The tensile capacity of the column itself was not was not exceeded, as evidenced from the fact that there was no damage in the column above the slab during the second phase of impact loading till collapse.

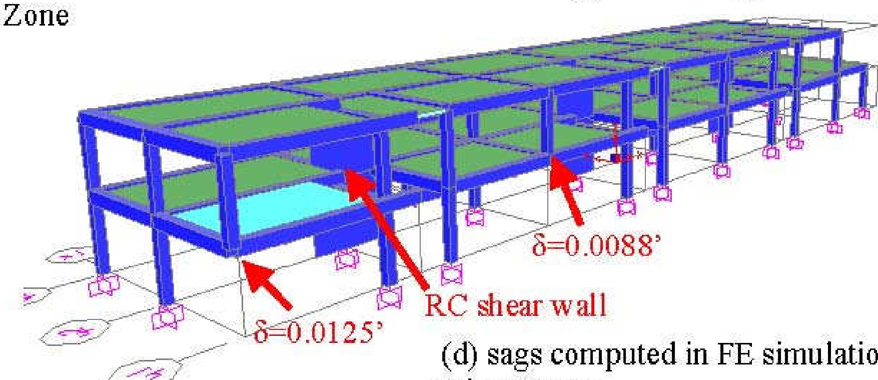
Another building of identical design was fitted with seismic accelerometers (Figure 5). Damage was induced in the structure by the phased removal of ground story columns (Figure 6a). Baseline (pre-damage) and post-damage measurements of the frequency response of the structure (FRF) (Figure 6b) were obtained by exciting the ground story columns with a 12 pound impact hammer with an inbuilt force transducer.



(a) Column removal choices consistent with GSA criteria

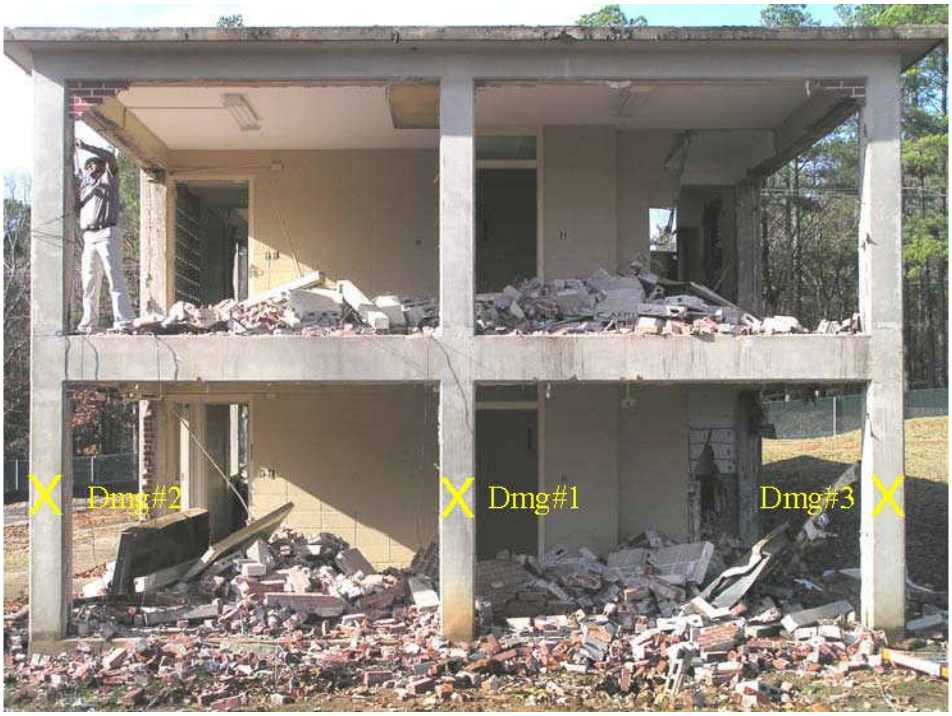
(b) corner column removal in field test
Hinge Zone

(c) corner sag measured in field test

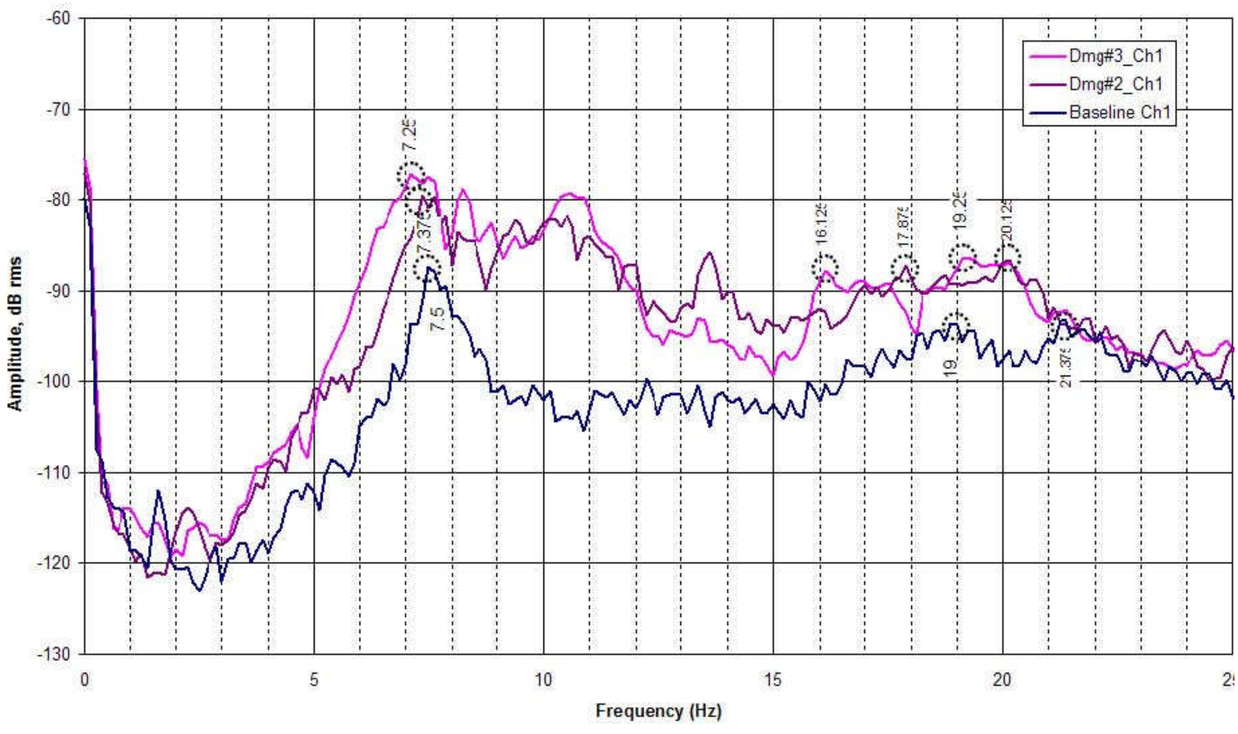


(d) sags computed in FE simulation
Hinge Zone

Figure 5: Corner column removal sequences during demolition of student apartment buildings and comparison of field sag measurements with FE simulation results



(a) Column removal sequence for end frame field test



(b) FRF from vibration measurements in field tests Hi Z

Figure 6: Comparison of FRF corresponding to various levels of damage

2. DECISION SUPPORT SYSTEM RESEARCH

The objective of the Decision Support level of research is to examine the potential benefits of using nano particle reinforced structural components in terms of improving life safety from a major blast event in a critical facility of significance to the State of Mississippi. The software, *E-Sim*, a proprietary software developed by Applied Research Associates, Inc., of Vicksburg, Mississippi, was used to perform an evacuation simulation for this facility. The application selected in this study is a nineteen story, high-profile government office building identified as critical by the Mississippi Office of Homeland Security. Figure 7 shows the 3D model and typical floor plans used to develop it.

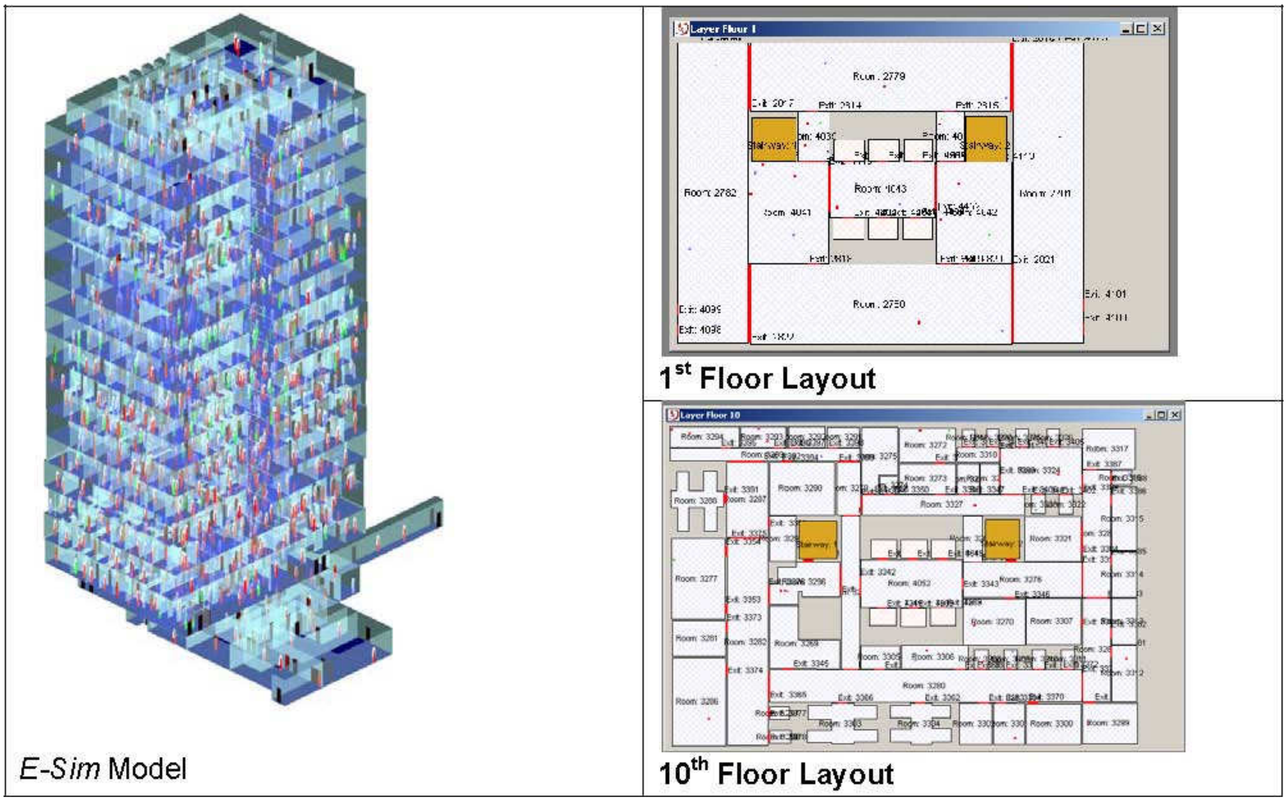


Figure 7: 3D model and typical floor plans used

Three scenario events were simulated to assess potential losses:

1. An evacuation drill of the existing building without any blast damage used as a baseline.
2. The building damaged from a blast without nano-particle reinforced composites.
3. The building damaged from a blast with nano-particle reinforced composites.

The location and size of the threat was determined based on ARA’s extensive experience and knowledge of typical explosive threats. The extent of damage to the facility was determined in conjunction with blast loads from the above threat through simplified analysis. The threat size and standoff distance used for the analysis were 100 lbs TNT and 7 meters.

The nanoparticle-reinforced facility is assumed to be constructed with 8-inch thick CMU walls, protected with 5 mm nylon 6,6-XGnP nanocomposites, which was considered to be a promising material at the time of the ARA model development. If the walls of the structure are upgraded for blast mitigation, it is assumed that windows are upgraded also. All windows were assumed to be upgraded to 1-inch laminated insulated glass units consisting of a ¼-inch annealed glass pane, a ½-inch air space, and a ¼-inch laminated annealed glass pane. The University of Mississippi provided ARA with the necessary material properties and retrofitted CMU wall panel resistance curves developed in the Structural Component level research. At the time of the ARA model development, only the AUTODYN simulation results were available.

To guide the evacuation scenarios, ARA developed a 3D blast model incorporating the wall protection system outlined above. Figure 8 shows the resulting estimated extent of damage from the above blast threat for cases representing an unprotected facility and a nano-particle reinforced facility.

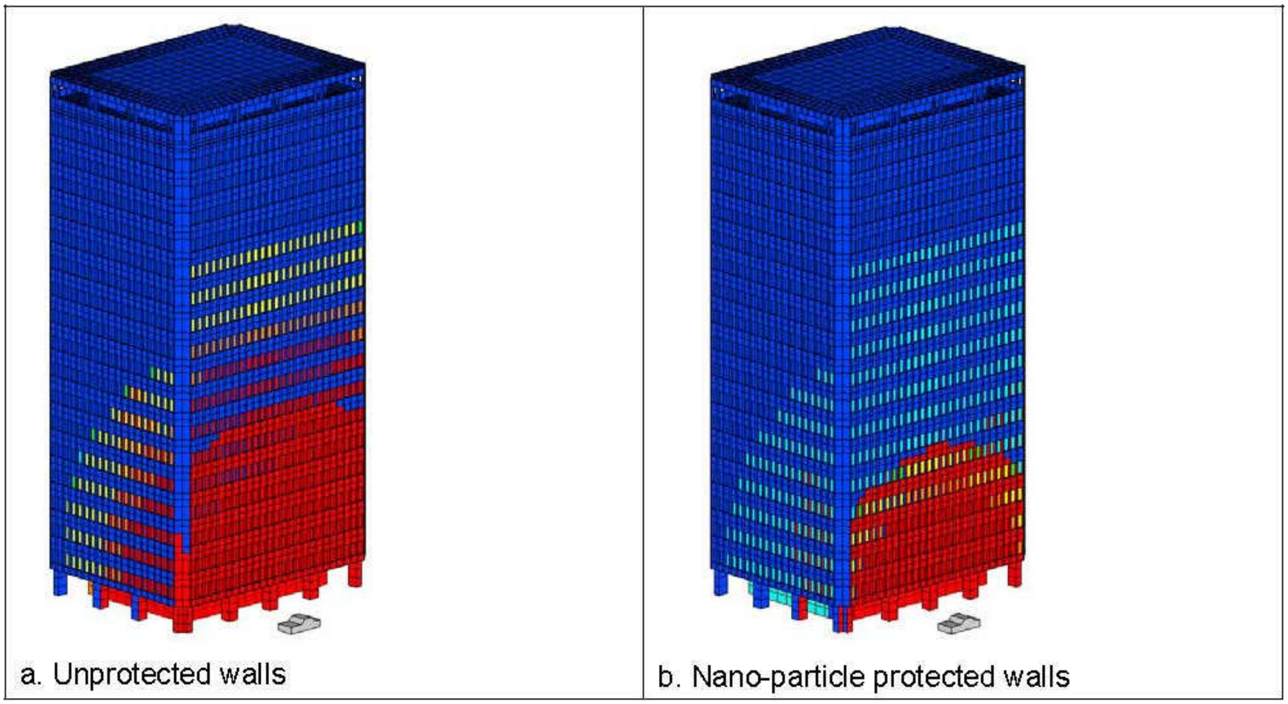


Figure 8: Simplified blast simulation to estimate extent of damage for evacuation scenarios

The heavily damaged areas shown in red were transferred into the E-Sim models as "kill-zones" where all agents are assumed to have been killed by the effects of the blast. While the retrofit scheme clearly mitigated the size of the kill zone, it is not considered capable of completely eliminating its formation. Such elimination is not out of the question but would presumably require another approach that may be cost-prohibitive.

The simulation assumes that some agents enter in the kill zone after the initial blast and could also be killed as a result of the "residual damage" to the area. At equal time intervals after the initial blast, fire/smoke was set to propagate through the facility floor by floor impeding agent progress causing more injuries and casualties to agents in those areas.

The baseline case consisted of an evacuation drill of the existing building under normal operating circumstances (without any blast damage). During a drill, the agents head to the designated "primary exits" rather than heading for the nearest exit as they do in the blast scenarios. For the building exposed to blast it took several minutes less than the base drill scenario to evacuate the building. The reduction in evacuation time is caused by agents picking the nearest exit of the building regardless of where it leads as they are in more of a “panic mode” at this point.

In the unretrofitted case, approximately 180 people were killed in the initial blast event; however, the largest concentration of people killed in the facility occurred in the two stairwells located at the center of the building. The large concentration of people killed in the stairwells was caused by significant blast damage to one of the stairwells and trampling caused by agents panicking. The building contains two large stairwells located toward the center of the facility. There are no exterior emergency exit stairwells in the facility. The layout of the stairwells leads to a potential for “bottlenecks” of occupants within the stairwells as people attempt to exit the building.

In the retrofitted case, approximately 80 people were killed in the initial blast event. As in the unretrofitted case, the largest concentration of people killed in the facility occurred in the two stairwells located at the center of the building. There was little if any blast damage to the stairwells in the retrofitted case, however, so most of the deaths were caused by trampling. If one or both of these stairwells were destroyed in a blast event, there would be no way to safely evacuate occupants from the building without taking huge risks to their health.

SUGGESTED STRUCTURE STABILIZATION METHOD

The previously discussed research addresses the issue of repairing structures to be less vulnerable to blast loadings. However, if a blast attack takes place, a quick stabilization procedure needs to be implemented. We propose taking the following steps.

Step 1: Develop a database of failure scenarios using recent advances in computer modeling technologies

We propose to identify to DHS suitable computer modeling technologies that reliably and effectively support the on-site, post-event, damage and stabilization needs assessment process. The goal is to be able to identify the potential progressive failure scenarios and to design the optimal stabilization schemes by allowing the computer model to easily remove or add structural members and examine the overall stability of the structure.

Candidate technologies will take advantage of existing or easily developed pre-event knowledge and/or simulation results databases for common building construction conditions. We will propose a rational methodology for implementing these databases in IED incident scenarios and for establishing the selection and deployment of the candidate materials and products identified instep 3 below. The candidate technologies and methodology will be benchmarked against IED incident scenarios and will satisfy performance objectives approved by DHS prior to their further consideration.

Candidate technologies will incorporate the results of the workshop and will incorporate some of the following characteristics:

1. Differentiation of rescue operations types and building structure destruction levels
2. Be applicable to a variety of commercial and industrial building construction having, for example, steel or concrete moment frames or concrete or masonry shear wall systems

3. Mechanics based material damage models for all critical load carrying heterogeneous structural components
4. Computational algorithms for implementing the material damage models in finite element codes
5. Coupling laws that integrate the damage models to overall strength and stiffness of the components
6. Computational methodologies that predict residual strength and stiffness of damaged critical components based on material as well as structural degradation
7. Physics based envelope of critical failure criteria for individual structural component of the overall structure to enable prediction of survivability, reparability, collapse or destruction of the system.

Step 2: Assess the degree and location of damage that needs immediate attention. Then prioritize needs for strengthening/repair

Given the urgency of the need of a post blast assessment tool, especially in cases of critical structural applications, a comprehensive approach that uses several different techniques in a systematic decision-making hierarchy is warranted. Such an approach would likely use rapid technologies for initial screening and call upon more involved methods for detailed defect characterization that would facilitate final decision-making as to the need for repair and for the evaluation of repairs. This concept and a limited sample application are described by Cloud, et al., 1999. Eventually, this process could be highly automated, and artificial intelligence could be incorporated.

The methods available for systematic NDE include optical techniques (digital speckle interferometry [DSI] and digital speckle shearography [DSS]), vibration testing (modal analysis), electrochemical impedance monitoring, thermal scanning, ultrasound (c-scan), eddy current, acoustic emission, x-ray, and others. These methods include some that can detect damage, or its impact, on a global (structural) scale, and others that can detect damage on a local scale. The investigators have detailed knowledge and some implementation experience with several of these techniques.

In practice, a rapid and simple technique, such as digital speckle interferometry, or vibration testing, will be first used to scan a structural component for anomalies that suggest flaws such as disbonds or cracks. Based on findings, a decision is made to use another technique, such as thermal imaging or dielectric measurement, to obtain more data about the anomaly. These data, taken together, might indicate that the anomaly might be safely ignored, should be repaired, or that more data, such as from localized ultrasound scanning, might be required.

Step 3: Conduct product test of repair technologies

During this Task, we propose to develop a material/technology database for quick selection of repair materials and technologies, and conduct up to three product test simulations based on preliminary computer and small-scale lab evaluations of repaired structure element (e.g., columns and connections). These test simulations will include testing protocols that will be approved by DHS prior to their delivery. Candidates for repair materials/technologies include:

1. Lightweight, rapidly deployable composites for shoring, pinning, bracing, and other temporary structural support purposes.
2. FRP (fiber reinforced plastic/polymer) for strengthening damaged columns and beams
3. Composite fixtures for strengthening column-beam connections
4. Polymer concrete for rapid concrete repair
5. Polymer sprays for strengthening walls and floors
6. high-strength, fast-set grouts (shotcrete) for foundation and soil stabilization
7. Higher Technologies:
    a. Low-cost nano particle additives, such as nano clay, POSS, grapheme platelets, Tripoli, cellulose whiskers, etc. to enhance the structural performance of polymer concrete composites.
    b. Quasi-3D woven fabric for better performing FRP.
    c. Nano particle additives, such as carbon nanotube and graphene, for health monitoring purposes, by mixing with repair material or applying as a thin layer, to enhance electrical or electromagnetic sensing capabilities.

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Monitoring Strategies for Rapid Assessment of Structural Condition and Stability Following a Terrorist Event

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ABSTRACT

Critical infrastructure systems, including government buildings, bridges, tunnels, pipelines, dams and levees, remain vulnerable to man-made hazards including improvised explosive devices detonated by terrorists. Current approaches to infrastructure protection largely focus on prevention and structural strengthening. However, after a terrorist explosion occurs, there is a dire need to rapidly assess the condition of the structure, quantify its stability, determine the extent of fire, and identify the location of structural inhabitants. This paper explores the opportunities that exist in deploying monitoring system technologies to provide real-time data and information to emergency first responders that are responsible for securing the structure and removing surviving inhabitants, all while ensuring the safety of first-responders.

INTRODUCTION

Explosive growth in the availability of sensing technology has occurred over the past two decades with innovative transducers and new approaches to data collection emerging. For example, the rapid development of microelectromechanical systems (MEMS) in the 1980's has led to low-cost, high-precision sensors (e.g., accelerometers, gas sensors, optic sensor) in impressively small and compact form factors (Kovacs, 1998). Similarly, the convergence of wireless communications, embedded computing, and sensing has led to the creation of low-cost wireless sensor networks for dense installation in large-scale civil structures (Lynch and Loh, 2006). Additional sensor technologies that have had a beneficial impact on the structural monitoring field includes fiber optic sensors (Measures, 2001), self-sensing multifunctional materials (Chung, 2003; Hou and Lynch, 2009), and acoustic/ultrasonic sensors (Achenbach, 1984), among others.

These advances have opened up exciting new opportunities for ubiquitous sensing of the built environment. For example, in seismic regions of the United States, critical structures (e.g., long-span bridges, hospitals, emergency response centers, skyscrapers) are instrumented with high-precision structural monitoring systems; when triggered by strong ground motion, these systems record the dynamic response of the structure (Celebi et al., 2004). Such systems have led to advances in understanding the behavior of structures to earthquakes and improved building codes. Structural health monitoring (SHM) systems have also been proposed by the structural engineering community. Similar to traditional monitoring systems, SHM systems consist of a sensing sub-system in which sensors are installed in a structure with sensor data communicated

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to a centralized data repository. However, unique to SHM systems is their ability to automate the interrogation of measurement data for identification of structural damage and deterioration. SHM systems potentially allow structural owners to adopt condition-based maintenance cycles in lieu of current schedule-based maintenance cycles. Condition-based maintenance is reactive to the real-time condition of a structure, thereby saving infrastructure owners time and money, both scarce resources. Given the potential of SHM to revolutionize infrastructure management, the National Institute of Standards and Technology (NIST) Technology Innovation Program (TIP) recently invested significant research funding to further develop SHM technology for infrastructure systems (Baum, 2009).

One area where sensing technology has not yet been widely adopted is in the area of infrastructure security. Recent terrorist activities including the Oklahoma City bombing (April 19, 1995) and World Trade Center collapse (September 11, 2001) underscore the vulnerability of critical infrastructure systems to man-made hazards (Figure 1). This paper explores the

(a) *(b)*

Figure 1: (a) Partial collapse of the Alfred P. Murrah Federal Building, Oklahoma City, Oklahoma shown on April 21, 2005; (b) aerial view of the World Trade Center ruins on September 15, 2001 (source: Department of Defense, *http://www.defenselink.mil/*).

opportunities that exist in deploying monitoring systems that can rapidly assess the condition and stability of a structure after a terrorist event (e.g., detonation of an improvised explosive device). Today, sensors exist that can be used to rapidly assess the structural condition of a structure, as well as the existence of emergency conditions including fire and smoke. In addition, there exist wireless data acquisition technologies that can communicate sensor data to first responders in a reliable and ad-hoc manner. Finally, cyberinfrastructure technology allows for the integration of sensor data and analytical models so that structural behavior (e.g., pending collapse) and the spread of fire can be modeled for improved on-site decision making by emergency responders.

INNOVATIVE SENSORS FOR CONDITION ASSESSMENT

Sensors for infrastructure monitoring during and after a terrorist event can be divided into three broad categories: 1) sensors for structural assessment; 2) sensors to monitor fire conditions (e.g., temperature and gases); 3) sensors to identify and track inhabitants. This section highlights the sensors that currently exist in addition to identifying opportunities to create new sensors that can meet the challenging demands of the application' environment (i.e., extreme shock and heat loads).

Structural Assessment

The global and local behavior of a structure must be sensed to predict its stability and structural condition (damaged versus undamaged). While many sensors exist for monitoring structural responses such as strain, tilt, displacements, and vibrations, very few of these sensors would be operable at elevated temperatures (for example, above 100ºC) nor would survive shock loading (for example, MEMS accelerometers would prove too delicate for shock loading). Hence, novel approaches to the design of sensors resistant to shock and high thermal loads are vital. Hardened packaging can also be developed to allow existing sensors to withstand the extreme environment. One particular technology well suited for high-thermal environments are sensors based on ceramics and carbon nanotube composite materials (Loh et al., 2007; Gregory and You, 2005); carbon nanotubes are robust in high heat environments due to the strength of the double carbon bonds that exist within the molecular structure.

Fire Assessment

Sensors that can determine the existence and movement of fire within a structure are critical to assessing fire induced changes in the structure and to managing emergency response personnel entering the structure. Temperature sensors can be used to identify the heat associated with a fire as well as the temperature of structural components. Gas sensors that can sense gaseous molecules (e.g., CO, CO_2) associated with combustion can be employed to understand the fire process. Sensors currently exist for measurement of temperature and gases (Pohle et al., 2007; Derbel, 2004; Harwood et al., 1991); however, opportunities exist to: enhance the sensitivity of sensors, miniaturize them through the use of nano- and micro-electromechanical systems (NEMS and MEMS), and reduce their fabrication costs. New sensing approaches based on optical detectors could also prove valuable to detecting fire conditions (Pinder, 2006; Pinder and Atreya, 2005).

Inhabitant Assessment

Tracking structural inhabitants is the first step toward evacuating them from a structure. Sensors are needed to monitor movement along egress paths including stairways and corridors. The specific transducers to be adopted include cameras and optical motion sensors. While such sensors can be found in the commercial market, innovative approaches are again needed to ensure they can survive the shock and high thermal loads associated with explosives and fire conditions.

HIGH DENSITY WIRELESS SENSOR NETWORKING

Wireless sensor networks are sufficiently mature that their recent deployment to large-scale civil structures, including large buildings and bridges, has been shown them to be convenient (i.e., easy to install), reliable and accurate (Lynch and Loh, 2006; Spencer et al., 2004; Chintalapudi et al., 2006). Furthermore, the ability for wireless sensors to process their own measurement data (e.g., autonomously identify structural damage) has been shown to be of great utility (Lynch, 2007). Due to their low costs and easy installations, wireless sensors offer one of the only viable technologies that allow buildings to be instrumented in high densities (i.e., hundreds of sensors in a single structure). As a result, they will be at the forefront of any monitoring system proposed for assessing the condition of infrastructure systems after terrorist activities. An additional benefit associated with wireless sensors is their ability to form communication links in an ad-hoc manner; this will play a critical role in facilitating the communication of data between sensors and first responders.

A low-cost wireless sensor node named Narada has been developed explicitly for infrastructure monitoring applications at the University of Michigan (Figure 2). Some unique features of Narada that render it optimally designed for infrastructure monitoring includes high resolution digitization (16-bit resolution), long communication ranges (300 m or greater), and low-power operation (less than 200 mW). An additional feature is the inclusion of an actuation interface operated by a 12-bit digital-to-analog converter; this interface allows the node to command actuators. A unique feature of wireless sensors is the inclusion of computational components in their design. For example, a low-power 8-bit microcontroller is included in the design of Narada. This microcontroller can be used to locally execute data interrogation algorithms embedded within the node (Zimmerman et al., 2008; Zimmerman et al., 2009). The Narada wireless sensor node could easily serve as the basis of a monitoring system intended to assess structural conditions after a terrorist explosion.

Emergency responders equipped with a wireless transceiver could establish peer-to-peer communication with the wireless sensors installed in the structure as shown in Figure 3. This

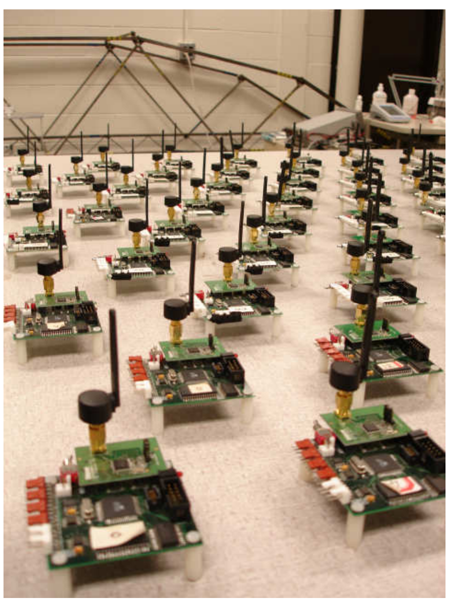

Figure 2: A dense set of Narada wireless sensors that were designed for infrastructure monitoring.

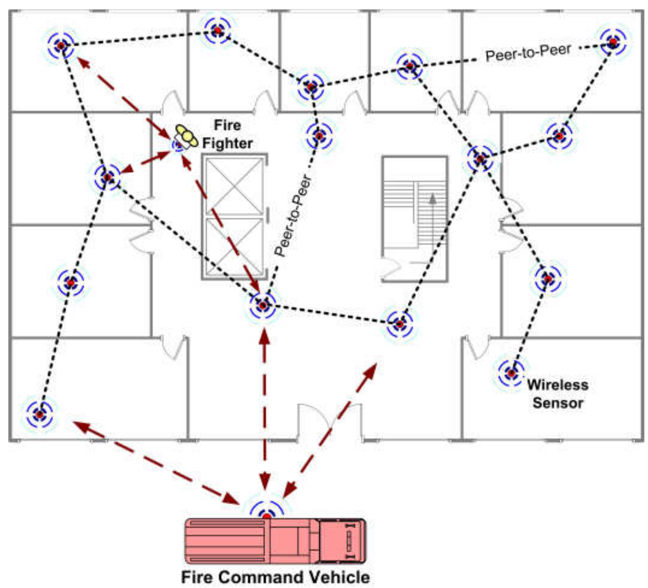

Figure 3: Proposed wireless connectivity between wireless sensors and emergency response personnel.

would allow the emergency response personnel to gain real-time information on the structural behavior as well as fire conditions. The availability of computational resources distributed within the wireless monitoring system can also be leveraged for automated sensor-based data processing. For example, embedded algorithms can be used to rapidly detect structural damage, predict the spread of fire, and detect imminent structural failure such as collapse. Such information can be forwarded to the emergency responder to allow for adaptation of their rescue efforts. In addition, the wireless transceiver coupled with the emergency responder would make it possible to track their location within the structure. For example, extensive use of radio signal strength indicators (RSSI) could be one mechanism for accurately tracking firefighters in structures (Zaruba et al., 2007).

CYBERINFRASTRUCTURE FOR UNIFICATION OF MEASUREMENTS AND SIMULATIONS

Advanced information technology systems including the internet, databases, on-line collaboration tools, social networking, and information feeds are often collectively known as cyberinfrastructure. Cyberinfrastructure can be a powerful technology for bridging the chasm that separates sensor data and simulation tools. A number of custom-designed cyberinfrastructures have recently been established for applications involving sensors, databases, and simulation tools (e.g., the National Science Foundation’s Network for Earthquake Engineering Simulation [NEES]). Similarly, cyberinfrastructure would provide a direct linkage between the sensor streams emanating from wireless sensors and simulation tools that are used to predict the behavior of the structure after a terrorist event.

Wireless sensors streaming data from a plethora of sensors are intended to feed data to simulation servers remotely distributed on the internet. With simulation tools inherently data-driven, they are enabled to provide real-time prediction of: 1) structural stability, 2) the spread of fire, and 3) input to intelligent egress management systems attempting to evacuate inhabitants. An example is shown in Figure 4; in this example, wireless sensors stream thermal sensor data

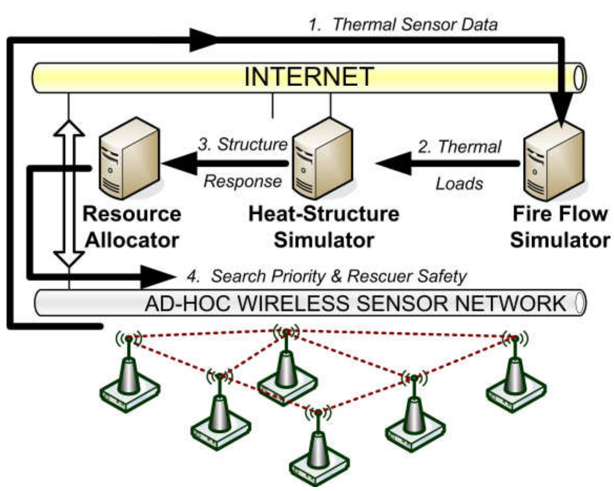

Figure 4: Proposed cyberinfrastructure for unifying sensed data and simulation tools within a real-time structural assessment system.

from an array of sensors in the structure. Through wireless linkage to an internet backbone (perhaps through a fire command vehicle), data is streamed to a fire simulation server where complex computational fluid dynamics (CFD) code is updated to current real-time conditions. Output of the fire model is passed to a CFD-structure model to predict the safety of the structure under existing thermal conditions. This provides an input to a resource allocation software element suggesting how fire fighters respond to fire, thereby enhancing their ability to get inhabitants out of the structure and to evacuate fire fighters if fire-induced collapse is probable.

CONCLUSIONS

The technological state of sensing and data acquisition technology is sufficiently mature to currently offer immediate solutions to monitoring the condition of buildings after a terrorist explosion. MEMS and wireless sensors are only some of the powerful new sensing technologies that allow for low-cost and dense sensing of the built environment. Furthermore, the integration of sensors with cyberinfrastructure tools allow data to be used in real-time to update predictive models that can alert emergency first-responders of imminent structural failures, the spread of fire and the location of inhabitants. Additional research is direly needed in the hardening of sensors for extreme shock and heat environments as well as in the actual integration of all of the monitoring system components described in this paper.

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Structural Health Monitoring: Overview and Challenges Ahead

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ABSTRACT

This presentation describes recent trends in structural health monitoring (SHM) at Sandia National Laboratories. Sandia's risk assessment methodology of Architectural Surety® is introduced. The use of valid senor data and validated models is described as a means of assessing damage that degrades the performance of high consequences structural systems. Recent advances in embedded sensors, computational simulation, damage detection algorithms, as well as prognostics and health management (PHM) tools offer new opportunities to monitor and assess structural performance margins. Along with these advances have come corresponding challenges in providing accurate SHM and PHM assessments to decision makers who must act on this information. Three recent examples of SHM systems at Sandia will be presented that demonstrate many of the current and future challenges faced in the field of structural health monitoring.

Structural Integrity Monitoring System for Detecting Imminent Collapse of Buildings

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KEYWORDS: Explosive Attack, Fire Damage, Structure Collapse, Dynamic Measurements, Structural Health Monitoring

ABSTRACT

During a disaster rescue mission, first responders, including firefighters, face significant risks because of uncertainties involving the collapse of structural components. The goal of this study is to develop a structural integrity monitoring system which is capable of detecting an imminent structure collapse caused by explosive attacks and/or fire. In this paper, the mechanical, thermal, and dynamic behavior of simply supported wood and aluminum beams subject to both static and thermal loads until failure are presented. Four Douglas Firewood beams and four 6061-T6 aluminum beams were tested. The test plan was motivated by firefighters' experiences that a noticeable level of wall, floor, or roof displacement and vibration happened before a structural collapse. This implies that an incipient structural collapse could be detected by monitoring the dynamic characteristics of the structural system. The test results from real-time dynamic measurements presented in this paper verify this observation.

INTRODUCTION

A building may collapse suddenly when it is subject to an abrupt change in the environment caused by, for instance, explosive attacks accompanied by fire. Structural collapse is one of the prime concerns during a rescue mission. First responders including firefighters face significant risk of injury or fatality when they enter the building to save disaster victims or to put out remaining pockets of fire. According to statistical data, structure collapse accounts for the maximum number of casualties among firefighters (Isner and Foley, 1996). First responders face significant risks because of uncertainties involving collapse of structural components. The development of a structural integrity monitoring system capable of detecting imminent structural collapse would benefit tremendously the rescue service community. Structural and system integrity monitoring is also of vital importance in many other applications. It can alleviate the risk of loss of life through the detection of structural damage soon enough to allow repair and prevent catastrophic failure. The technology developed will not only reduce the loss of firefighters' lives but will also be applied to numerous industries.

One important aspect of developing such a structural integrity monitoring system is to understand the structural behavior of buildings subject to fire. The current practice in designing buildings for fire is based on fire resistance ratings as specified in the ASTM E119 Standard (1989). This practice does not represent the actual structural performance during a real fire. It does not take into account temperature distributions, restraints against thermal expansion, system deformation, local failure, redistribution of moment resistance, etc. The behaviors of structural members, such as beams, columns, slabs, or connections, under elevated temperature were studied by Liu (1999), Ma and Makelainen (2000), Milke (1999), Olawale and Plank (1988), Poh and Bennetts (1995), Sakumoto (1999), and Sha (1998). Modeling and response predictions of entire frames or buildings in fire were studied by Bailey (1998), Bresler and Iding (1980), Iding and Bresler (1984), and Saab and Nethercot (1991).

Another important aspect for developing the structural integrity monitoring system is to explore the existing nondestructive testing (NDT) techniques. Possible NDT techniques for the monitoring system for firefighters include vibration measurements, ultrasonic techniques, infrared monitoring, acoustic emissions, magnetic measurements, strain/temperature measurements, large displacement monitoring, video monitoring, etc. Most of these techniques can only be applied to damage detection in a local area, such as in a beam or a slab, except for the vibration measurements (Stubbs and Diaz, 1994). Dynamics-based Vibration measurement methods have been applied to damage detection and condition assessment of full-scale structural systems with varying levels of success. Kim and Stubbs (1995) presented a damage detection algorithm based on changes in a few mode shapes to locate and estimate the severity of damage in a 90-foot high offshore jacket steel platform structure. Stubbs and Diaz (1994) evaluated the impact of quality function deployment (QFD) utilization on the development of a dynamics-based nondestructive damage detection algorithm for aerospace structures. Chan et al. (1995) formulated an improved condensation method for detection of local damage in terms of story-stiffness reduction due to damage of columns in multistory frame buildings. Brownjohn and Xia (2000) investigated the assessment of the Safti Link Bridge, a 328-foot curved cable-stayed landmark bridge in Singapore, via model updating to improve the numerical predictions of the results. These papers indicate that vibration measurement methods could be applied to full-scale structural systems for damage detection.

To achieve the goal of developing the structural integrity monitoring system, we first studied the mechanical, thermal, and dynamical behavior of simply supported wood and aluminum beams subject to both static and thermal loads until failure. Douglas Fir wood beams and 6061-T6 aluminum beams were tested. The test plan was motivated by firefighters’ experiences that a noticeable level of wall, floor, or roof displacement and vibration occurs prior to a structural collapse. This implies that an incipient structural collapse due to fire damage could be detected by monitoring the dynamic characteristics of the structural system using a vibration modal analysis method.

In this paper, the structural integrity monitoring system to be developed is described first. The experimental setup and the test results including displacements, strains, temperatures, and dynamic measurements of the aluminum and wood beams are then presented.

STRUCTURAL INTEGRITY MONITORING SYSTEM

The structural integrity monitoring system to be developed is essentially an early warning system for disaster rescuers that detects structural damage induced and provides an indication of imminent collapse of a building. The conceptual design of the system is described as following. Sensors are installed inside or outside the building and send signals continuously to the receiver in the mobile monitoring center deployed near the scene. The central computer unit in the mobile center analyzes the signals and judges if any part of the building is about to collapse. In case something critical is detected, the warning module emits emergency warning signals to the receiver carried by each rescuer. An alternative is to have each rescuer carry a sensor and a portable monitoring unit. As soon as the unit senses a critical condition in the area near the rescuer, warning beep sounds will go off to signal for evacuation.

The requirements for the monitoring system are as follows: 1) The system is able to determine if a structure component is about to collapse and issue warning to the rescuers with sufficient time to evacuate. 2) The system must have a mobile field deployment capability that can be set up quickly and easily at a disaster scene. 3) Sensors must be able to withstand extremely harsh environments, such as elevated temperatures, toxic gases, intensive interference of signals due to various noises, and low visibility due to smoke. 4) Signals from sensors should be gathered wirelessly rather than using cables. 5) The monitoring system has to rely completely on the measurements taken during an incident since it is not practical to have measurements on all buildings in good condition to provide a reference database due to a huge number of existing buildings involved. 6) The system must be able to conduct real-time measurements as well as instant analysis and judgment on the spot.

EXPERIMENTAL PLAN

During a fire caused by an explosive attack, the rate of deterioration in material strength and stiffness increases with an increase in the temperature. It is expected that this rate of change in structural stiffness prior to collapse would be rapid enough to cause a dynamic-like action leading to structural vibrations. Some firefighters have reported that they experienced a noticeable level of vibration before the onset of collapse. This implies that an incipient collapse of a structure due to fire damage may be detected by monitoring the dynamic characteristics of the structural system using a vibration modal analysis method.

A test plan was designed to verify this observation and to better understand the structural behavior under elevated temperatures. The main purpose of the test plan is to study: 1. the structural behavior subject to fire, 2. the rate of deterioration, 3. if noticeable changes in response and vibration exist before collapse, and 4. the timing of collapse. Two series of tests on aluminum and wood beams were conducted. The first test series was to apply a concentrated static load at midspan of simply supported beams in step increases until the failure occurred. Strains and displacements were measured. Acoustic emission technique was used to monitor intensity of “popping” during the first several beam tests, but was discontinued because not much acoustic activity was observed. Natural frequencies and mode shapes were also acquired using an accelerometer. The entire progress of the test was recorded using video monitoring. In another test series, loading at approximately one half the beam capacity was applied first, and the test article was then heated at midspan using heat lamps until the failure occurred. In addition to the measurements taken in the first test series, temperatures at various locations along the beam were measured as well using thermocouples.

To facilitate the vibration measurements, natural frequencies and mode shapes of the first several lower modes of vibration were computed numerically before the test using a finite element program. The material properties are assumed linear elastic and isotropic for the analysis. Only bending modes in the vertical direction are considered. The loading point at midspan is assumed constrained in the vertical direction because the loading head is applied at that location. The calculated natural frequencies and mode shapes are shown in Figure 1. These results give us the information about the frequency range for the measurement and the information about the node point locations of each mode where vibration measurements, or points of impact, shall not be taken so as to prevent from missing that mode shape.

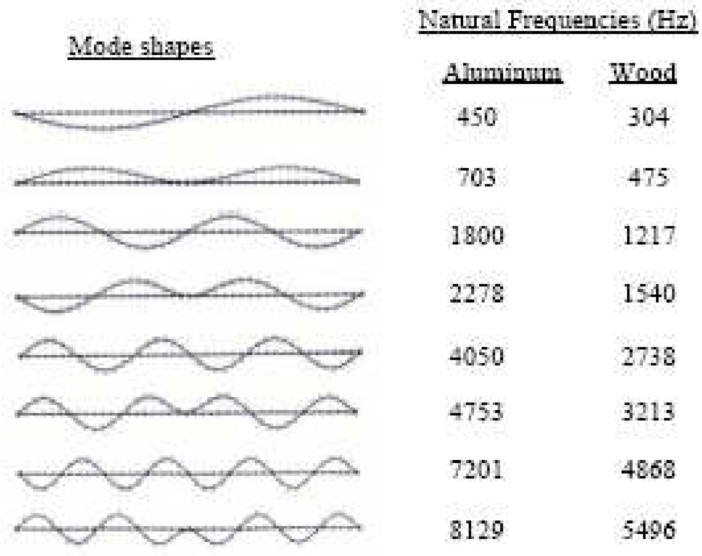


Figure 1: Mode shapes and natural frequencies from finite element analysis

EXECUTION OF THE EXPERIMENTAL PLAN

A total of eight articles, four aluminum alloy (6061-T6) beams and four wood (Douglas Fir) beams, were tested based on the test plan described in the previous section. The wood beams were carefully filtered to ensure that “clear” straight-grained samples without knots, cross grain, and splits were selected. A list of the representative material properties of the tested articles is presented in Table 1.

Table 1: Material properties of tested articles

Aluminum Alloy 6061-T6		
Modulus of elasticity, E	10.0x106 8.0x106	psi at ambient psi at 500°F
Poisson's ratio, ν	0.33	
Density, ρ Coefficient of thermal expansion, α	0.098 13.1x10-6	lb/in3 inch/inch/°F at 68 to 212°F
Specific heat, c	0.214	Btu/lb/°F at 68°F
Thermal conductivity, K	96.5	Btu/ft/hr/°F
Tensile strength, σ	45.0	ksi (yield)
	40.0	ksi (ultimate) at 75°F
Wood, Douglas Fir		
Modulus of elasticity, E	1.49 to 1.95 x 106	psi
Modulus of rupture	11,900 to 12,400	psi
Specific gravity	0.45	
Tensile strength	15,600	psi

The experimental investigation was so planned to simulate the conditions of a structure being exposed to extremely high heat. Figures 2 and 3 show the test configuration and apparatus' setup of the experiment. The beams were supported such that they are free to rotate about a transverse axis, and (free to) expand in any direction. Each article spanned 40 inches between supports, with cross-sections measured 1” × 1-7/16” (width × height) for the wood beams and 1” × 2” for the aluminum beams. Measurements were taken at various locations to monitor the displacement, strain and temperature profiles, and the dynamic response of the tested beam. Strain gauges of type wk-13-250BG-350, designed to withstand a maximum temperature of 750°F, and twelve Omega-SA1, type E thermal couples were mounted on the beam surface for the measurements.

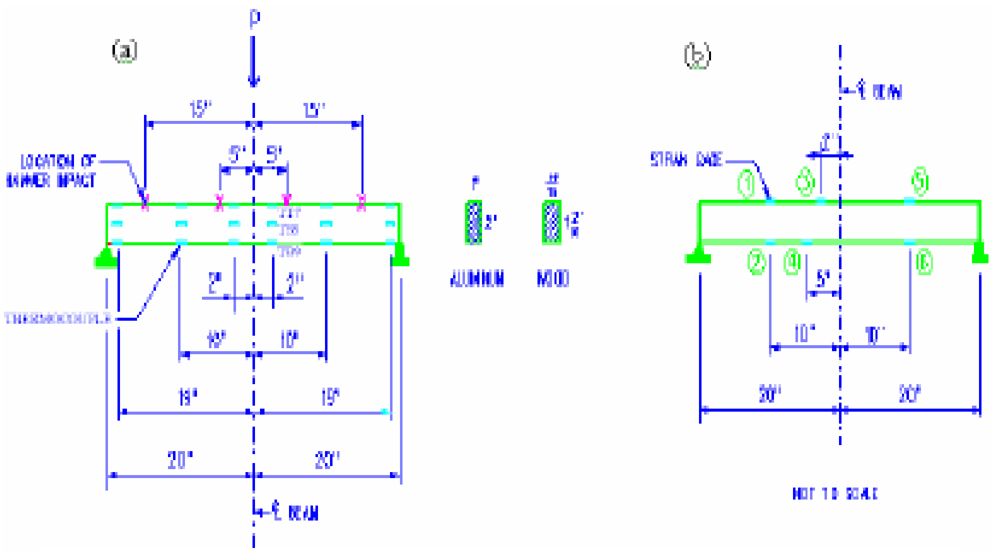


Figure 2: Test configurations for wood beam and Aluminum beam tests. (A) Locations of thermal couples and excitation points for dynamic measurement; (b) Strain page locations

The tests were performed on a SATEC-K120 loading machine. First, a static load of 140 lbs, which is approximately one half of the ultimate strength of the wood beams, was applied at mid-span of the simply supported article. While the static load was kept constant for the duration of the test, a thermal load was applied from the bottom of each beam in the mid-span region at a rate of approximate 10°F/min until the beam failed. Two 6.5-inch heat lamps generating a maximum total heat output of 700 watts were utilized to create the thermal effects. As the temperature in the wood beam increased, physical properties of the beam changed in the forms from reduction in modulus of elasticity (E) to reduction in yielding and ultimate strengths (σy and σu). As a result, although the static load remained unchanged, the beam eventually failed due to the deterioration of material when the temperature reached a certain level.

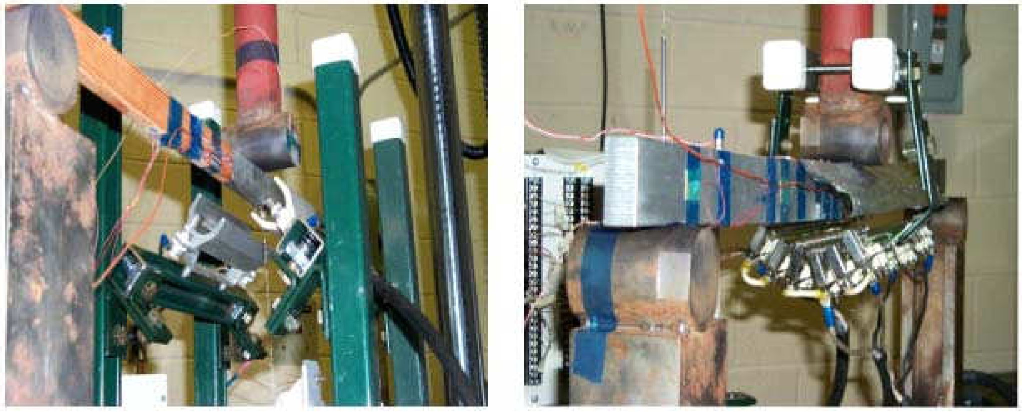


Figure 3: Photos of test setup of wood and aluminum beams

Static loads with higher magnitude were applied to the aluminum beams. The loads were 2000 lb, 3000 lb, and 3250 lb, representing approximately 50%, 75%, and 80%, of the beams' ultimate load capacity, respectively. The thermal effects were created by six 14-inch heat lamps with 500 watts each, providing a maximum total heat output of 3000 watts. Heating lamps were so arranged and adjusted to ensure that heat is exerted at the bottom face and conducted upward through the height of the beam. Other measures were also taken to reduce the heat radiation to the surrounding air.

In case of each of the tested beams, small impacts were applied at every 50°F temperature increment for dynamic measurements. A singular homogenous impulse was generated using a modal impact hammer at four locations along the beam as shown in Figure 2(a). The impact locations were selected to be away from node points to prevent from missing that mode shape. The dynamic response to the excitation was acquired and recorded. A single-axis ICP354B17 accelerometer was mounted on the tested member at the same location where the first left impact was exerted to obtain and then deliver dynamic data to a Structural Dynamic Analyzer (SDA), which recorded and processed the input and output signals. A Hewlette Parker HP3566A Analyzer, along with data acquisition software, CATA-x, developed by LMS International, Inc. (Belgium) served the purposes. The arrangement of four impact locations with one accelerometer taking measurements at one location is equivalent to having one impact location with measurements at four different locations. During the modal testing, the average of three impacts was taken at each excitation point to minimize the effects of random noises. In addition to acquiring the frequency response functions (FRF), real time accelerometer response was recorded on magnetic tape using a Sony-PC116 Instrumentation Cassette Recorder. The entire test process was also recorded on VHS tapes using a PELCO video camera.

DISPLACEMENT, STRAIN, AND TEMPERATURE MEASUREMENTS

Two typical sets of results data, one from the wood beam test and the other from the aluminum beam test, are presented in Figures 4 and 5. When temperature in the wood beams, in most cases, was raised to 250°F or above, the member exhibited sudden and obvious failure. As observed in Figure 6, failure occurred in forms of separation of the wood fibers or physical "fracturing" of the fibers. With an average modulus of rupture of 12,000 psi at ambient temperature, the beams were expected to be able to withstand a transverse load of 280 lbs at midspan. Being a natural material, variation in properties is common in wood even for clear and homogeneous samples. The mechanical properties of timber depend highly on its natural characteristics such as grain arrangement and sizes, moisture level, age, chemical contents etc. Thus the amount of heat required to cause failure varied noticeably between the four tested beams. Because wood is considered as a poor heat-conduction material, heat transfer along the longitudinal direction of the beam is limited. Thermal effects were concentrated within a localized area near the center portion directly above the heat source. A summary of the final temperature profile of the wood beams at failure is illustrated in Figure 7.

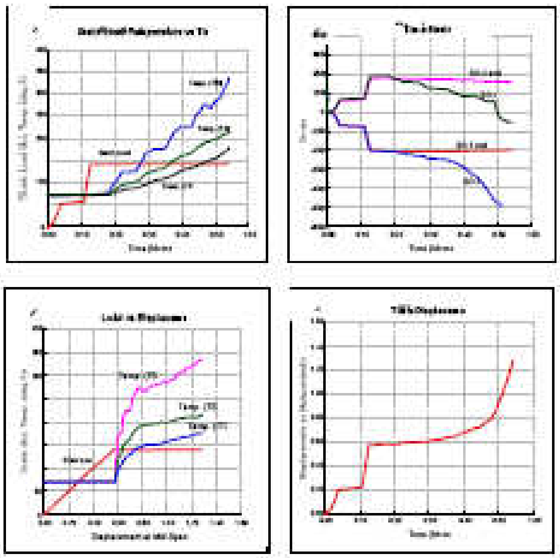


Figure 4: Typical result data from wood beam tests (test #4)

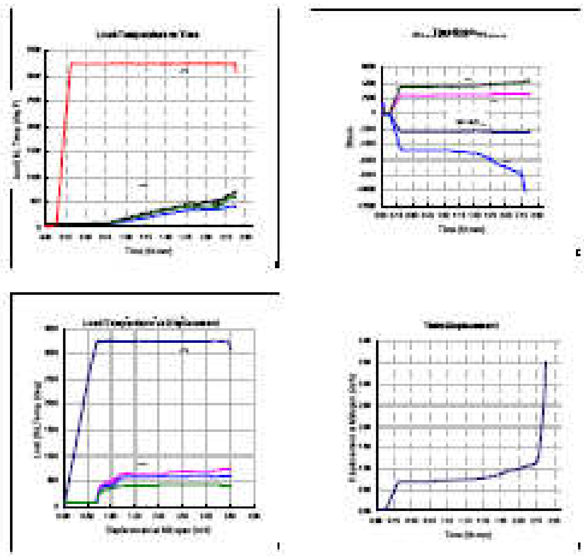


Figure 5: Typical result data from aluminum beam tests (test #3)

Figure 6: Photos of failed wood and aluminum beams

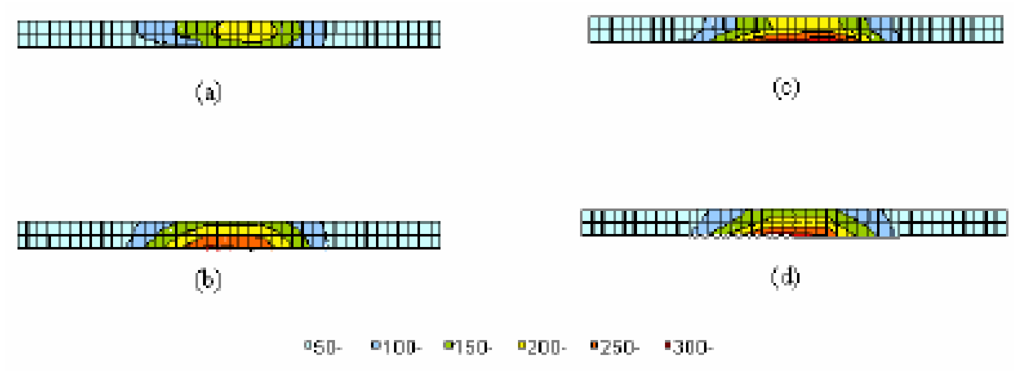


Figure 7: Summary of the final temperature profile of the wood beams at failure

It can be seen from the load versus displacement curves in Figure 4 that the wood beam appeared to have a sudden failure when the temperature (TB9) was raised to about 270°F. At this point, the midspan deflection started to increase rapidly. This can also be seen clearly from the time versus displacement curve Figure 4 that the displacement rate increased to a much higher value at the time of about 50 minutes. Unlike the wood beams, aluminum beams experienced large deformation rather than sudden fracture when the temperature was raised (see Figure 6). The tests were stopped when the deflection at midspan of each beam reached 3.5 inches to prevent possible equipment damage.

After a static load of 2500 lb and 3000 lb was applied to the first and second aluminum beams, respectively, the temperature was then increased. In both cases, the static loads were increased at the end to bring the beams to failure (i.e., midspan deflection reached 3.5”) because the heating device setup could not heat up the beam to a high enough level. The static load applied at the beginning of the test on the third beam was increased to 3250 lb and the heat lamps were rearranged. When temperature in the top center section of the beam exceeded about 400°F, the member started to deflect at a rapid rate. Because of heat dissipation to the air, a localized area with high concentration of heat was formed in each of the aluminum beams directly over the thermal input. This high temperature region is somehow bigger compared to that of the wood beams. As the temperature was increased beyond 500°F, three thermal couples experienced minor separation from the member surface. As a result, temperature measured at these locations does not reflect the true condition. Comparisons with data from similar locations were made to provide the best estimations. A summary of the final temperature profile of the tested beams at failure is shown in Figure 8.

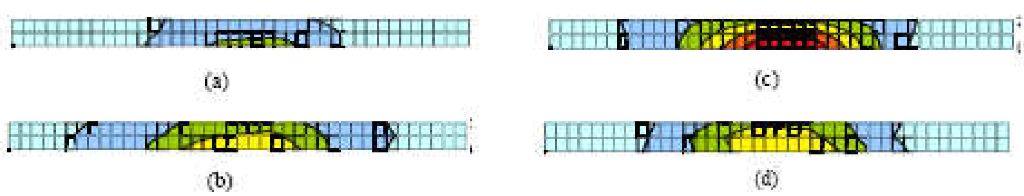


Figure 8: Temperature Contour of aluminum beams at failure (a) test #1, (b) test #2 (c) test #3 and (d) test #4

DYNAMIC MEASUREMENTS

The dynamic measurements were taken at ambient temperature and beyond that, at 50°F increments. One typical set of result data at its MIF and FRF formats is presented in Figures 9 and 10. In each measurement, five dominant modes of vibration were identified. Frequencies corresponding to these mode shapes are shown in Table 2 and Figures 11 and 12. During the test, the load head was moved to maintain the static load constant when the beam material was weakened by an increase in the temperature. The movement of the load head might somehow affect the pattern of frequency changes. Table 2 and Figure 12 show that the natural frequency had little or no fluctuations at the first mode of vibration, regardless of the changes in temperature. At other modes, natural frequencies exhibited a consistent declination as the temperature was raised. However, the appearance of the mode shapes remained unchanged until the last measurement, when the temperature reached 250°F beyond ambient the ambient temperature. It was the approximate temperature recorded before the beam fractured due to the combined effects of static load and thermal load. In the first and second low frequency modes, each mode shape was split into two. As a result, two new mode shapes with similar magnitudes as their neighboring modes had formed. As for the higher frequency mode shapes, a new peak was appearing at the end of the fifth mode. The new mode had a frequency of 1450 Hz, although its magnitude was not as large as the neighboring one.

Wood is a layered, highly non-isotropic material. As it was approaching failure, although an obvious fracture was not yet observed, it’s reasonable to suspect that local damages in some of the fibers already occurred at a smaller scale. The abnormal appearance of the mode shapes could have been the result of such characteristics. At large displacements, the boundary conditions of the beam were affected by beam rotations at the two end supports. Changes in boundary conditions cause changes in the structural stiffness and thus trigger changes in the natural frequencies and the mode shapes. Further investigation of the frequency change and the change of mode shapes due to damages should be carried out to study the failure mechanism and timing in a greater depth. Wood performed poorly in conducting both heat and vibratory waves. When excited from one end of the beam, signal was not able to be transmitted through the fibers to the other end. It would start to fade near mid-span, where the second constraint of movement was located. This was especially true when associated with high frequencies (from mode 3 and after). Waveforms in the second half of the beam were nearly unrecognizable.

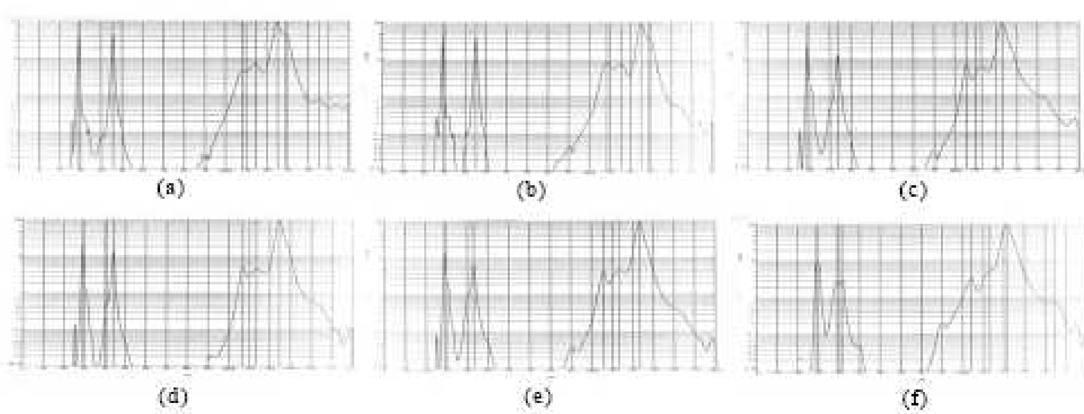


Figure 9: Complex MIF of wood beam 1 at different temperatures beyond ambient: (a) ambient, (b) 50°F, (c) 100°F, (d) 150°F, (e) 200°F, and (f) 250°F

Table 2: Dynamic measurement of wood beam #1 in elevated temperatures
(a) natural frequencies; (b) damping ratio

(a)

Mode of Vibration	Load = 140 lb, Room Temp.	Load = 140 lb, Temp. = 50 F	Load = 140 lb, Temp. = 100 F	Load = 140 lb, Temp. = 150 F	Load = 140 lb, Temp. = 200 F	Load = 140 lb, Temp. = 250 F
	Frequency (Hz)	Frequency (Hz)	Frequency (Hz)	Frequency (Hz)	Frequency (Hz)	Frequency (Hz)
1	291	290	287	289	289	287
2	457	450	436	439	432	419
3	1077	1077	1057	1063	1058	1047
4	1148	1153	1133	1133	1132	1136
5	1249	1249	1229	1246	1233	1211

(b)

Mode of Vibration	Load = 140 lb, Room Temp.	Load = 140 lb, 50 F above	Load = 140 lb, 100 F above	Load = 140 lb, 150 F above	Load = 140 lb, 200 F above	Load = 140 lb, 250 F above
	Damping (%)	Damping (%)	Damping (%)	Damping (%)	Damping (%)	Damping (%)
1	1.782	1.476	1.712	1.688	1.736	2.473
2	1.361	1.556	1.912	1.637	2.011	3.539
3	2.196	2.570	1.658	1.636	1.728	1.956
4	1.283	1.319	0.691	0.805	0.781	0.261
5	1.803	1.686	2.079	1.813	1.927	2.402

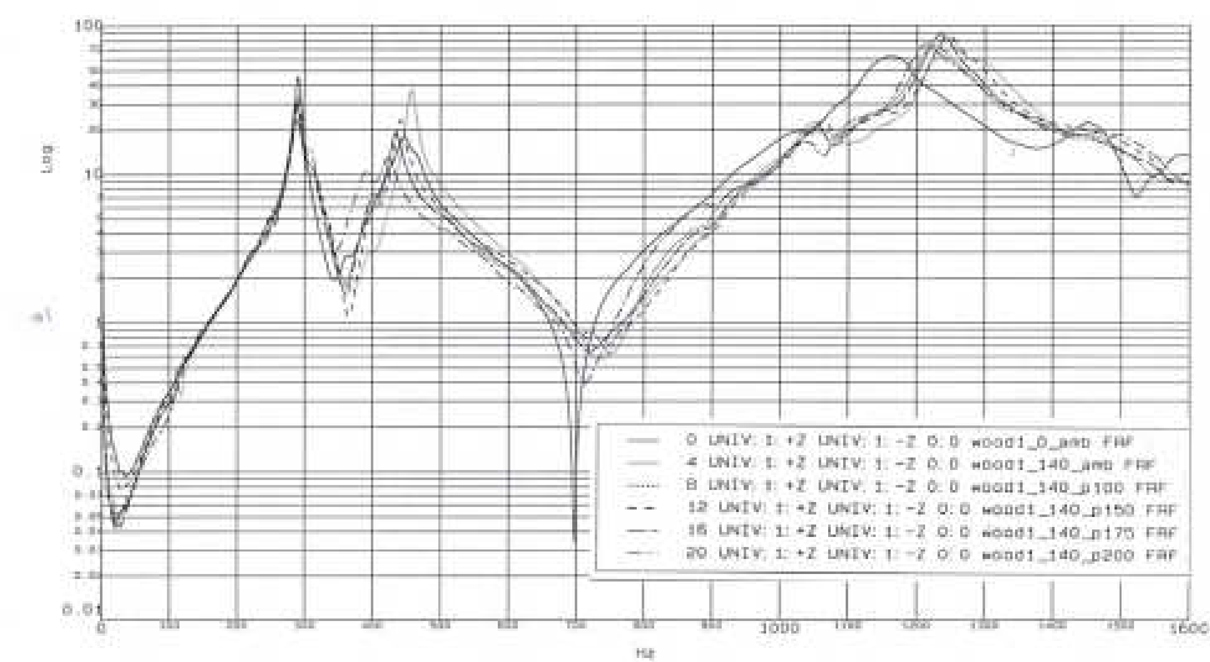
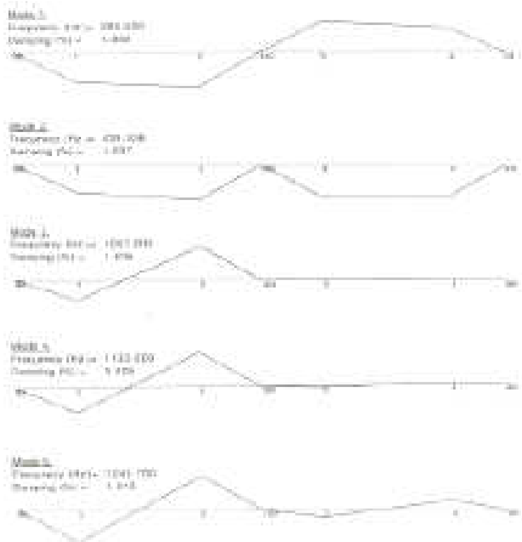


Figure 10: Frequency response functions of wood beam 1 before any loading, and at static load at midspan = 140 lb and temperatures beyond ambient = 0°F, 100°F, 150°F, 200°F, and 250°F



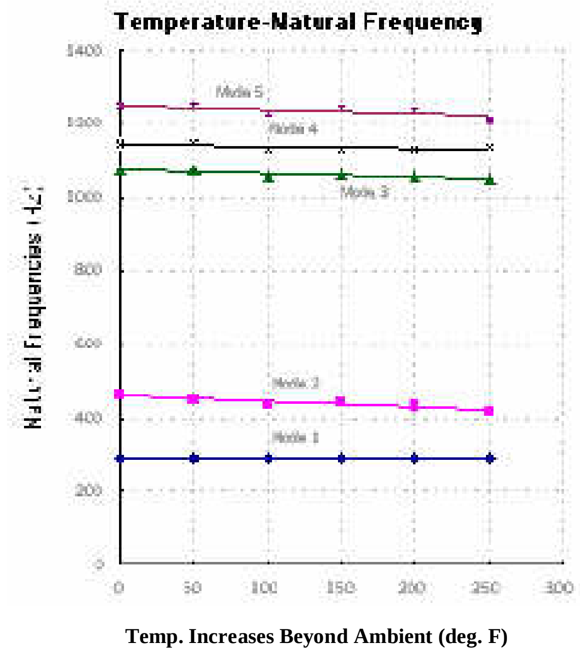


Figure 11: Typical mode shapes of dynamic vibration of wood beam (beam 1), at temperature = 150°F beyond ambient; static load at midspan = 140 lb

Figure 12: Decreasing of natural frequencies with respect to raising temperature (wood beam 1)

REAL TIME ACCELEROMETER MEASUREMENTS

The real time accelerometer response is one of the major focuses of this study because it provides information as to whether noticeable vibrations caused by the temperature increase can be detected before the beams fail. Close examination of the accelerometer responses on magnetic tape showed a clear pattern of vibrations in the wood beams prior to their collapse. As shown in Figure 13, the big surges between the 240th second and the 420th second, counted from the start of the real-time recording, correspond to the last hammer impacts applied to the beam. Small surges in vibration occurred throughout the test and became more frequent as the beam approached failure. From the 725th second, the beam showed seismic-like behavior with nonuniform magnitudes, possibly caused by rapid vibratory movement. At the 740th second, a sudden spike with a magnitude of 0.4 was recorded. Fifty five seconds later, a second surge with a magnitude of 1.9 occurred. No external hammer impact was applied during this time period. Each of these surges likely represents the failure of one or more wood fibers in the beam. To better understand what happened, the displacement at midspan versus time curve is also shown in Figure 13. It can be seen that the spikes at the 740th second and the 795th second correspond to increases in the rate of displacement. The test ended at about 830 seconds, when the beam failed. This indicates that a self-vibration caused by temperature rise can be detected before beam failure. The detected spikes at the 740th and 795th second gave warnings preceding the collapse.

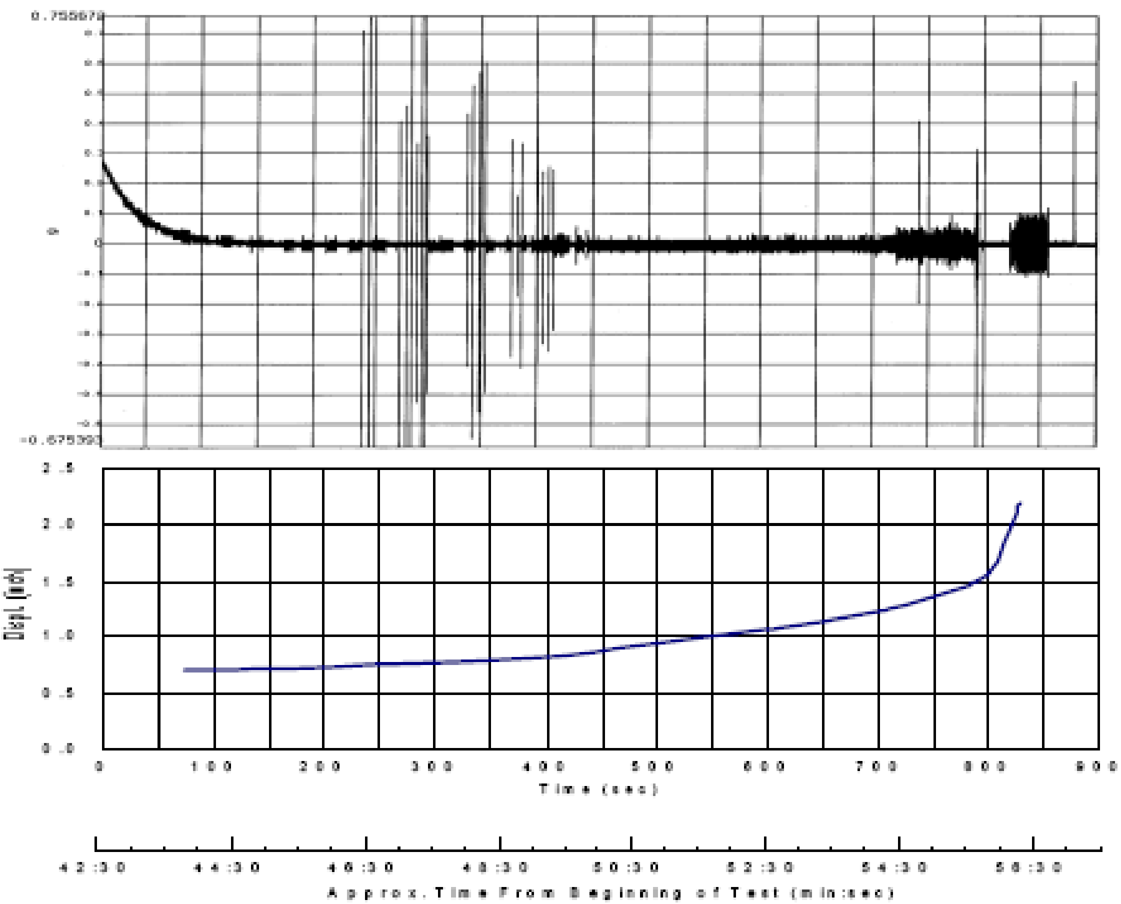


Figure 13: Real-time dynamic response record of wood beam #4. Top: Real time dynamic response; Center: Displacement vs. Time (from beginning of real-time recording) curve; Bottom: Time scale (from beginning of load test)

CONCLUSIONS

This research studied the mechanical, thermal, and dynamic behaviors of structures under elevated temperature. A particular focus was to study if structural collapse caused by fire could be detected ahead of time using dynamics-based measurement methods. The results form the tests on simply supported wood beams show that as the temperature rises, the natural frequencies decrease and the mode shapes alter. The real time accelerometer responses show that self-vibrations can be detected before the beams fail as a result of high temperature. These results evidently indicate that structure collapse due to fire damage can be detected by monitoring the dynamic characteristics of the structure system.

ACKNOWLEDGMENTS

The authors acknowledge financial support from NASA Marshall Space Flight Center. Special thanks to Dr. Michael L. Tinker, Mr. Marc Verhage, Ms. Kathy Kappus, Mr. Houston Hammac, Mr. Jason Huddleston and Mr. Russel Parks for their supports in conducting the experiments.

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Shoring Stabilization of Buildings in an Urban Search & Rescue Environment

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ABSTRACT

At a collapsed building incident, search and rescue operations necessitate quick action if survivors are to be extricated from the structure. However, these operations must be conducted while managing the risk to the rescuers themselves. Rescue trained engineers (Structures Specialists) have the knowledge and capability to assess the damaged structure and recommend hazard mitigation plans to reduce the risk to rescuers. There are several mitigation methods (Avoid, Remove, Minimize Exposure, Monitor, and Shore) available to manage the risk. This paper presents an overview of building assessment and mitigation methods that are part of the Department of Homeland Security Federal Emergency Management Agency's Urban Search & Rescue program. Building stabilization using emergency shoring is emphasized and effective shoring techniques, objectives of shoring, and experimental testing of shoring systems are presented.

INTRODUCTION

Emergency shoring used in urban search and rescue incidents is defined as the temporary stabilization or re-support of damaged structural members or systems subject to continued movement or collapse. The shoring support is applied as necessary to only a section of, or structural element of, or a part of the compromised structure. Shoring is used in order to provide a safer and more efficient working environment while conducting trapped victim search and rescue operations. If hazards exist that cannot be mitigated by other means (i.e., avoidance, minimizing exposure, or removal), then shoring can be used to reduce the risk environment for the collapse incident's victims, as well as the collapse trained rescue forces.

This paper describes the building stabilization shoring techniques used in the Department of Homeland Security Federal Emergency Management Agency Urban Search & Rescue (DHS/FEMA US&R) program. The Structures Specialist (rescue trained engineer) on the DHS/FEMA US&R Task Force is responsible for recommending appropriate mitigation methods for reduced risk rescue operations. Through the U.S. Army Corps of Engineers Urban Search & Rescue Structures Specialist training programs, shoring techniques and the physical testing of shoring systems has resulted in standard shoring designs and shoring design capacities for building stabilization in collapse incidents.

ASSESSING THE STRUCTURE, MANAGING THE RISK, AND MITIGATING THE HAZARDS

When confronted with a structural collapse incident, many issues and concerns must be assessed when developing a rescue operations plan. The Structures Specialist (engineer) assisting at the site is concerned primarily with how extensive the collapse is, what caused the collapse, type of construction, including floor system, redundancy and ductility, age of the structure, fire damage or other material damage, and the possibility of additional loading such as wind and rain, aftershocks, or secondary explosions. The rescuers at the site are focused on locating and extricating victims trapped in the building. The rescue operation's objective is to expedite rescue of victims while reducing the risk to victims and rescuers to an acceptable level.

To effectively implement the rescue operation plan, there are several options available to reduce risk and expedite rescue of victims. Generally, the five main options are to AVOID, REMOVE, MINIMIZE EXPOSURE, MONITOR, and SHORE the hazards.

Avoid the Hazard

Avoiding the hazard is just as it sounds. If there is no immediate need to be in a specific dangerous area, that area is cordoned off and personnel do not enter. An example would be to cordon off the front of a building where there is collapse debris that could slough off the building or a parapet that is subject to falling.

Remove the Hazard

Removing a hazard is also like it sounds. One of the most dangerous situations for rescuers is falling debris or objects from overhead. Thus, by removing the object, the hazard is removed. Another example is a leaning non-load-bearing wall or a leaning brick chimney. After consideration of the effects, the wall or chimney can be pulled down, removing the fall shadow hazard in the operation's area.

Minimize Exposure to the Hazard

When time is critical, or other hazard reduction methods are not justified, the risk can be reduced by minimizing exposure of personnel to a dangerous area. For instance, if a large building is racked laterally, shoring that building would require much time, effort, and materials. If there are live victims in the structure, rescuers can minimize the number of personnel in the building, the time in the building and the higher risk areas in the building. Another example is if there is a victim trapped in a building and the time for extrication is estimated to be short. Then the time required to shore the building does not justify the short exposure time for the rescuers to extricate the victim.

Monitor the Hazard

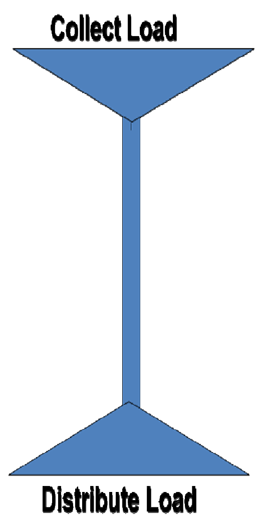
Monitoring the time-dependent movement of a structure as operations continue comes in many forms, including using surveying equipment to monitor building movements, strain gauge indicators to monitor crack widths, digital levels to monitor plumbness or rotations of walls or components, wireless rotation sensors for monitoring dangerous areas, and others. Monitoring can be used to track global building movement, element or component movement, debris field movement, or very localized area deformations. Monitoring can be used independent or in conjunction with other forms of hazard reduction methods. Monitoring is usually quick to set up and does not require significant resources.

Shore the Hazard

The most costly in terms of personnel resources, material resources, and time resources, and the main topic of this paper, is mitigating the hazard by stabilizing the structure with shoring. When there is considerable risk to rescue personnel and the rescuers will need to work in the high risk area for a significant amount of time, shoring stabilization of the structure is warranted.

OBJECTIVES OF RESCUE SHORING OPERATIONS

The main and paramount objective of emergency building shores is to properly maintain the existing strength and integrity of any and all structurally damaged or unstable elements; such as, but not limited to, beams, joists, girders, columns, arches, headers, and bearing walls. This is accomplished by using shoring to properly and effectively “receive and collect” the potentially unstabilizing collapse loads and “transmit and or distribute” these loads to a safer load path through the remaining structure. Figure 1 illustrates this load transfer. Loads tend to gather in specific local areas after a collapse, causing a heavy concentrated load effect, overstressing the existing local structural elements, and must be transferred eventually to stable ground. For instance, this is common when interiors of building floor systems collapse onto lower floors. Voids (cantilever, lean-to, V-shaped, and A-framed voids) are created in the collapse areas that may contain live victims. The collapse patterns create concentrated loads on the lower floors.



Requirements for Effective Shoring
Adjustability
Positive Connections
Lateral Bracing
Ductility
Warning of Overload

Figure 1: Vertical Shore Principles and Characteristics

Depending on the type of structure, these loads can be transferred or distributed to structural elements in the remaining part of the building that are sound and capable of handling the additional collapse caused loads. Another type of building damage that creates hazards to the victims and rescue personnel is lateral drift of elements or floor stories. Here, lateral shoring systems are used with the same objective of receive and collect the load and transfer or distribute this load to a safer load path through the remaining structure and eventually to the ground.

CHARACTERISTICS OF EFFECTIVE SHORING

Unlike simple gravity shoring typically used in the construction industry, emergency building shores must be constructed as a robust system and be able to withstand uncertain load and deformation demands. The possibility of secondary or progressive collapse is a primary concern during any structural collapse rescue operation. The demands placed on the shoring and the potential risk to the victims and rescuers require shoring systems that are stable and ductile in their performance. An additional crucial requirement for emergency shoring is that it provides a warning system that clearly indicates when the shoring itself is overloaded (an overload fuse).

Figure 2 illustrates a vertical shore that meets the requirements for stability and ductility with a warning fuse to notify of danger in the case of an overload. A top header beam collects the load from above, vertical posts transfer the load downward, and the bottom sole plate distributes the concentrated loads to the underlying supporting surface. Each one or these items is important for the success of the shoring system. The key to shores is to collect the loads from a damaged area, funnel it through the post system, and distribute the load to the ground or other suitable structural elements. The posts are “fit-up” between the header beams and sole plates during erection using wedges as shown in Figure 2.

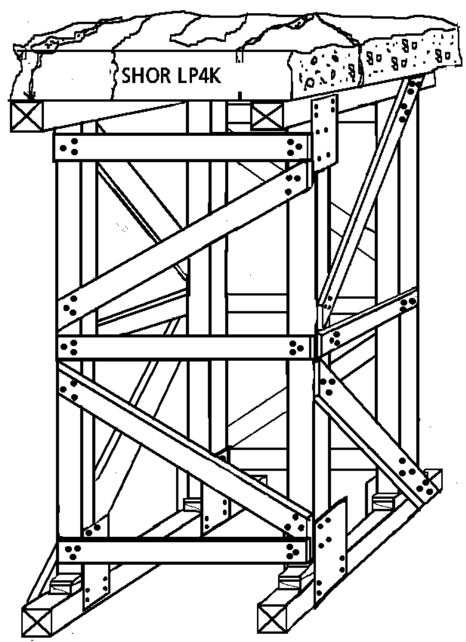


Figure 2: Vertical 3-Dimensional Laced Post Shore

One form of stability is directly related to the unbraced length of the post columns. To prevent buckling of the posts, the length to width ratio should be no more than 50 and ideally should be limited to 25 if possible. Limiting to this slenderness ensures that the posts do not buckle before the ultimate strength of the shore is obtained. Thus, lateral bracing is required for the posts in both directions to reduce the unbraced length as shown in Figure 2.

However, there are additional demands on emergency shoring that must be considered that are not prevalent in construction type shoring. Since there is a possibility of secondary or progressive collapse, there is also the possibility of lateral load or deformation demands on the vertical shores. Thus, the ideal shore should be 3-dimensional in terms of width and depth in addition to the height.

Figure 2 has four posts laced together to form the width and depth that supplies the lateral stability. If the shore is built with only two posts, as shown in Figure 3, it has the width, but not the depth, and would be susceptible to lateral instability if a load or deformation demand develops in the depth direction. Thus, the shore shown in Figure 3 is classified as a 2-dimensional shore. In emergency shoring operations, 2-dimensional shores may be installed for rapid access, but they should be modified (by lacing together with an adjacent 2-dimensional shore) into 3-dimensional shores as operations continue.

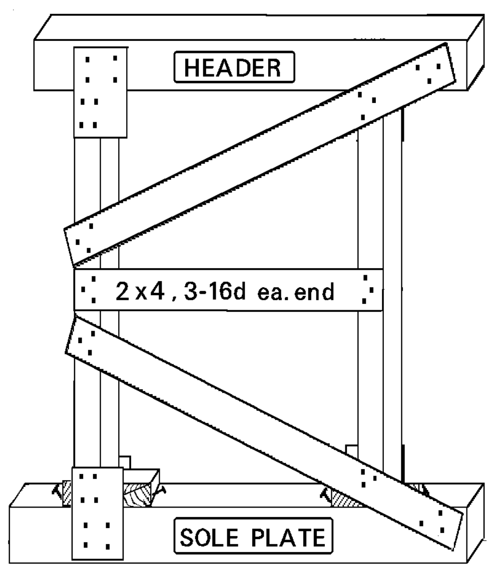


Figure 3: Vertical 2-Dimensional Two-Post Shore

Ductility in the shore is achieved by the failure mode at the ultimate strength of the shore. The posts are in compression parallel to the grain of the wood. However, the post compressive load transfers to the header beam, sole plate and wedges as a compressive load perpendicular to the grain. The perpendicular compressive strength is significantly lower than the parallel compressive strength, and the failure mode is the ultimate compressive strength of the header beam, sole plate, and/or wedges. This ultimate strength is lower than the buckling strength of the posts, and the failure mode is ductile with significant deformation and warning. Figure 4 illustrates the failure of the header, and Figure 5 shows the failure of the wedges at the ultimate strength.

Figure 4: Header Splitting at the Ultimate Strength

Figure 5: Cupping of the Wedges at the Ultimate Strength

A benefit of the ductile failure mode is that it also provides warning when the shore is overloaded. The cupping of the wedges and the splitting of the header or sole beam as shown in Figures 4 and 5 initiates when the shore is loaded to approximately one-half the ultimate strength. Given that the design load for the shore is typically one-third of the ultimate strength, when these indicators appear, the load on the shore is greater than the design load. Thus, the header beam, sole plate, and wedges act as a structural fuse. When the fuse indicators appear, then appropriate action can be implemented.

Figures 1 through 5 present vertical shore systems, but lateral shores also have the same objectives, use the same general techniques and must meet the same requirements for stability, ductility, and a warning system. Figure 6 illustrates a lateral “raker” shore. The shore is 3-dimensional with the two independent rakers laced together. The vertical wall plate (against the wall) and the wedges have perpendicular to grain compressive stresses for the ductility and the warning system.

Figure 6: Lateral 3-Dimensional Raker Shore

EXPERIMENTAL TESTING OF SHORE SYSTEMS

Through the U.S. Army Corps of Engineer' Structures Specialist training program, shoring systems have been tested to examine their ultimate strength capacity, the failure mode behavior, and ductility and stability performance. As testing over the years progressed and reliable results verified DHS/FEMA US&R shoring techniques, variations in the design were developed and tested to examine alternative shoring designs for implementation. Although both vertical and lateral shores have been tested, and lateral load applied to vertical shores has been tested, only vertically loaded (gravity) vertical shore tests and results will be discussed here to demonstrate vertical shoring performance. Table 1 presents the test results of 16 vertical shore tests. The variation between the tests is the method of lacing (2x4, 2x6, or plywood).

Table 1 Vertical Laced Post Shore Tests

Shore Designation	Stability Lacing	Ultimate Failure Load
LP-1	2x4	100k
LP-2	2x4	90k+
LP-11	2x4	90k+
LP-12	2x4	90k+
LP-21	2x6	110k+
LP-22	2x6	90k+
LP-24	2x4	100k+
LP-31	2x4	103k
LP-41, 61	2x4	103k
LP-51	2x4	90k
LP-32	24"Ply	103k
LP-42	12"Ply	83k
LP-52	24"Ply	100k
LP-53	24"Ply	88k
LP-62	24"Ply	115k
LP-63	24"Ply	144k

Figure 7a shows a typical laced post shore (as shown in Figure 2) in a vertical load testing machine. The shore has four 4x4 posts and the lacing (diagonals and horizontal stability bracing) is made of 2x4 lumber. The header and sole beams are 4x4, and sets of 2x4 wedges under each of the posts are used to "fit-up" or pressure the shore in place. Figure 7b shows an alternative vertical laced post where the stability bracing (lacing) is supplied by 24-inch wide sheets of plywood (plywood laced post). The remainder of the shoring system (header, etc.) is the same as the typical laced post system. Both of these vertical posts are 3-dimensional, having a width (4 ft) and a depth (4 ft) along with a nominal 12 ft height. Several other variations (depth, amount of lacing bracing, amount of plywood) of 3-dimensional vertical shore alternatives have also been tested to study their performance.

Figure 7a Laced Post Shore

Figure 7b Plywood Laced Post Shore

Figure 7: Vertical 3-Dimensional Post Shores in Testing Machine

According to the DHS/FEMA US&R shoring criteria, a four post 4x4 laced post has an allowable shoring design capacity of 32 kips (8 kips/post). The allowable design capacity is limited by the compressive stresses applied to the header beam, sole plate or the wedges, where the compressive stress is perpendicular to the grain. Compressive crushing of the grain is a ductile failure mode. By careful design of the lacing, buckling of the posts (non-ductile) prior to a large deformation and overload is avoided by limiting the slenderness.

The results in Table 1 show that the ultimate strength of the laced post shore is approximately three or more times the allowable design load of 32 kips. This is an appropriate level of safety for rescue operations. However, an important behavioral aspect of the laced post shore is the ductility and the warning the shore indicates when the shore is overloaded. Cupping of the wedges consistently occurs around two times the design load. Cupping of the wedges is demonstrated in Figure 8a. As rescue operations continue and the shores are routinely rechecked, an indication of an overload on a shore warrants attention immediately. The header and sole beam are also indicators of overload. Figure 8b illustrates an overloaded header beam. Header splitting usually occurs around two to three times the allowable design load.

Ductility can be considered as the deflection at the ultimate strength. The shores typically deflected 1.5 to 2 inches at the failure load. The deformation is primarily from the compressive stresses perpendicular to the grain in the header beam, sole plate, and wedges as demonstrated in Figure 8.

The ultimate failure mode, after the warning indicators have developed and the ductility has been used, is usually buckling of the posts at a weak spot such as a knot. This is shown in Figure 9. The shoring design and implementation practice is that the warning system will alert the Structures Specialist to the overload and appropriate actions will be taken.

Wedge Deformation

Header Deformation

Figure 8: Header and Wedge Deformation at the Ultimate Strength

Figure 9: Eventual Buckling of the Posts at Failure

SUMMARY

After a building collapse, the DHS/FEMA Urban Search & Rescue response involves the location, rescue (extrication), and initial medical stabilization of victims trapped in confined spaces. The Structures Specialist on the team performs various structural assessments and develops mitigation plans during these incident operations. The Structures Specialist has undergone considerable training in response operations, structural collapse assessment, monitoring, and hazard mitigation. The training is necessary for the Structures Specialist to have a positive contribution to the incident response and to ensure effective and proper application of mitigation measures. Shoring is one of the tools to mitigate hazards.

Techniques and Equipment for Monitoring Damaged Structures

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ABSTRACT

At a collapsed or damaged building incident, search and rescue operations may require monitoring of hazards to help reduce the risk to the rescuers. This is often the case when the hazards to the rescuers cannot be mitigated using other means. Monitoring techniques employed by Federal Emergency Management Agency (FEMA) Urban Search and Rescue (US&R) personnel vary in sophistication from a simple plumb to a wireless biaxial tiltmeter system. The technique used by the Rescue Trained Professional Engineer (Structures Specialist) at a particular incident depends on the type of the building and expected collapse behavior, the anticipated length of the rescue operation, and the anticipated timing of how the hazard will fail. This paper describes monitoring techniques used in the FEMA US&R System.

INTRODUCTION

Monitoring the time-dependent movement of a structure as operations continue comes in many forms, including using surveying equipment to monitor building movements, strain gauge indicators to monitor crack widths, digital levels to monitor plumbness or rotations of walls or components, wireless rotation sensors for monitoring dangerous areas, and others, some as simple as a plumb bob. Monitoring can be used to track global building movement, element or component movement, debris field movement, or very localized area movement. Monitoring can be used independently or in conjunction with other forms of hazard reduction methods. To be effective these devices must be continually read and accompanied by an effective alarm system that activates an efficient evacuation plan. Monitoring is usually quick to set up and does not require significant resources.

The Structures Specialist (engineer) on the Federal Emergency Management Agency Urban Search & Rescue (FEMA US&R) team is responsible for recommending appropriate mitigation methods for reduced risk rescue operations. Through the U.S. Army Corps of Engineers Urban Search & Rescue Structures Specialist training programs and others, mitigation techniques to minimize rescue personnel exposure to hazards have been developed and refined to create a standard among various Federal, State, and local responding agencies. The primary methods for minimizing the exposure to hazards is of course avoidance and/or removal of the hazard, though in search and rescue operations these techniques are often not feasible or not possible given timing or conditions of the disaster event. In these cases, monitoring the hazard to provide early warning of failure is the only method of minimizing the risk to personnel working within a hazardous environment.

MONITORING CONSIDERATIONS

In order to successful monitor a damaged building and provide an adequate warning system for US&R operations, several considerations must be addressed prior to implementing a monitoring plan. First, it must be determined if monitoring can provide the level of assurance necessary to reduce the risk to an acceptable level. Structures that exhibit rapid brittle failure behavior may not provide adequate time for a warning for US&R personnel, regardless of the monitoring method. Second, it must be determined how the building will collapse. Different buildings will have different collapse patterns depending on their structural configurations and the event causing the damage. A DHS/FEMA or USACE Structures Specialist is specifically trained in identifying potential collapse patterns for a wide range of building types. Knowing the collapse pattern, it can be determined if the movement will be primarily translational or rotational. This determination will lead to identification of hazards that can be monitored and what monitoring tools will be the most effective in capturing the movement of the hazard.

The Structures Specialist must first quickly visualize the collapse mode of a suspected hazard. This leads to further identification of what hazard needs to be monitored, why, and for how long monitoring should continue. The direction of the expected movement needs to be determined so that correct displacements are monitored. One must determine which of the available monitoring tools will best determine the expected movement. Angular rotation can be measured using several tools. The accurate measurement of lateral and vertical translation will need to be carefully planned. Safety and sightlines will probably influence the location of the monitoring devices on the structure. Identifying survey targets on a damaged structure may not be possible, so finding appropriate targets that will telegraph incipient movement is critical.

MONITORING TOOLS

The monitor tools used for DHS/FEMA US&R operations vary in their complexity and use, depending on the type and degree of structural damage. The following tools have been used to monitor damaged structures for changes in stability:

- Engineers' Theodolite or Total Station
- Electronic Tiltmeter System
- Electronic Level
- Laser Pointers or Level
- Plumb Bob
- Crack Measuring Device
- Other Devices

Theodolites and Total Stations

These surveying instruments have been successfully used to monitor damaged structures, including falling and collapse hazards. The use of the theodolite, which can accurately measure angles in both horizontal and vertical plane, has recently given way to the total station, which can measure distances in addition to angles. The total stations that are part of the DHS/FEMA and USACE equipment cache use a pulse laser, enabling distance measurement with or without a reflector prism or target. The ability to measure to a reflectorless surface greatly reduces the risk to US&R personnel, as prisms or reflectors do not have to be mounted on the damaged structure.

For reliable and repeatable results, it is necessary to establish control points, such as back sight lines, that allow for re-setup of the instrument. This may be problematic following earthquake aftershocks, when many structures and ground surfaces have been moved and possibly disrupted. The control points need to be secure locations that are fully visible from the monitoring location and will not be moved during rescue operations.

The advantage of the total station over the theodolite is that it allows for the overlay of a three-dimensional grid or coordinate system of the building site. The coordinate system is set orthogonal to the building, which allows for quick interpretation of measurements. In addition, any number of total stations can be set up in the same coordinate system. This improves the accuracy of the measurements and helps reduce false reports.

The total station has not been used on any major deployment since its introduction into the FEMA US&R system in 2006. Theodolites, which are no longer a cache requirement, have been successfully used on several major incidents, including the Oklahoma City bombing and the collapse of the World Trade Center twin towers. However, theodolites have often been used poorly and without reference marks, as well as without proper records and warning systems. As a result, erroneous readings have caused false alarms to be sounded. This is, obviously, an intolerable condition that can undermine the creditability of a monitoring system. The most common cause of false readings is inadvertent moving of the instrument set up on a tripod. One needs to establish effective barrier systems around the monitoring station.

The advantages of the total station can be summarized as:

- Observation without contacting structure
- Make distant observations
- Ability to zoom in on structure
- Observe many points from one location

The disadvantages are:

- Cost of instrument ($6,500)
- Requirement for trained operators
- Readings not always intuitive
- Need stable reference/control points
- May be difficult to establish post-aftershock control
- Cannot use with full face mask

Wireless Biaxial Tiltmeter System

A Wireless Building Monitoring System (WBMS) has been developed by Exponent (Engineering and Scientific Consulting) for use in FEMA US&R monitoring operations. Each system consists of four bi-directional tiltmeter sensors that can be remotely read to either one of two HP iPAQ Pocket PC or a laptop computer. There are also two spread-spectrum receivers having a range to 1,000 feet if the signal is not obstructed by heavy structures or metal.

Software developed for the WBMS is set to poll each sensor at 10-second intervals. It checks the signal for interference, and an audible ping is heard as each sensor reports good data. A lower frequency "clunk" is heard if a sensor is not operating properly or turned off. The software can be set to trigger an alarm at any preset angle change (alarm can be sounded through an earpiece). The tiltmeters are sensitive to angle changes of 0.05 degrees. Twelve-volt batteries provide 7 days of continuous monitoring.

The advantages of the WBMS can be summarized as:

- Can monitor four or more locations at once
- Very accurate and can set alarm for any amount of movement
- Uses a portable receiving/alarm system
- Allows for remote observations (up to 1,000 ft)
- Can use with a full face mask if conditions warrant

Disadvantages of the WBMS are:

- High cost ($18,000 per full-system [2005])
- Need qualified, technician operator
- Need planned, periodic battery recharge system
- Need to place sensors on structure
- They have remote, 7-day, 12-volt batteries

Electronic Levels

Commercially available electronic (carpenter) levels are available that are sensitive to an angle change of 0.1 degree, with digital readout. They can be mounted on a structure, the angle recorded, and any subsequent change would then be read by any task force member. To prevent exposure to personnel in a hazard zone, binoculars or telescopes can be used to read the digital readouts. The electronic levels must be mounted rigidly to the structure to prevent false indications. Various mounting methods have been employed such as fabricated steel mounting angles that can either be epoxy glued or screwed to the structures.

Most electronic levels are supplied with a battery saver feature that turns the instrument off in 5 minutes if no change in angle is sensed. This feature must be disabled if it is to be useful in US&R monitoring applications to prevent the need to continuously wakeup or reset the device.

The advantages of electronic levels can be summarized as:

- Low cost
- Long battery life (approximately 40 hours)
- Easy to read

Some of the disadvantages include:

- Not as accurate as tiltmeter
- Need to place on structure

- Need to place two in each location to measure angle change in N-S + E-W direction
- Need to dedicate someone to read them—line of sight
- Need to modify battery saver function

Laser Levels

Laser levels may also be used to measure an angle change of about 0.1 degree. Various brands and models are commercially available and most are relatively inexpensive. Both single and triple beam (three-axis) configurations are available. Most laser levels come with magnets embedded in their bottom surface, marking mounting easier.

To use a laser level for structural monitoring, a target must be placed on the structure within 75 feet of the device. The target can be as simple as an "X" inscribed on the structure. It is possible to use a three-beam level with two targets to observe movement in two directions. Battery life can be an issue, as some models have only 12 hours of continuous use.

The advantages of a laser level can be summarized as:

- Low cost
- Easy to read

The disadvantages are:

- Not as accurate as WBMS
- Need to be placed on structure
- Need to place two targets for each location to measure angle change in two perpendicular directions
- Someone to read them and have the proper line of sight
- Need to replace batteries

Plumb Bob

A simple plumb bob and string can be used for small to moderate structures to determine changes in position of one story from another, between a story and the ground, or between an upper part of the wall and the ground. This can allow one to measure and record the changes in a leaning structure when no other device is available. A rock on a string has been used when no other means were available.

The advantages of a plumb bob are that it is inexpensive and simple to use. No special skills are required. Disadvantages of the plumb bob are that personnel must attach the plumb bob to the structure and constantly observe it, and that it can be affected by the wind.

Crack Measuring Devices

Cracks in concrete or masonry shearwalls or concrete moment frame beams can be monitored in several ways. It is important to know if the cracks in a damaged building are of a constant width or enlarging. Methods that have been used include:

- Marking an “X” across the crack with the center on the crack. Significant lateral movement changes can be observed.
- Placing folded paper in cracks or use automobile thickness gauges (0.004” to 0.025”) to measure a specific location.
- Adhesive or other tape may be placed across the joint to measure change, but dusty conditions may prevent tape from adhering. (Need to be prepared to clean surfaces if this is only option that is available.)
- Two parallel sticks (rulers) can be taped across a crack with a perpendicular line being drawn across both of them (or existing lines on two rulers can be aligned). If the crack changes width, then the originally straight line will be offset.
- Plastic gauges may be placed across cracks to indicate change. (Mount with quick set epoxy or concrete screws.)

Note that if a structure has significant changes in temperature, the cracks will change widths due to the temperature change. The larger the structure, the larger the change in the crack width.

Seismic Trigger Device

Available devises can be installed at the site to sense the initial primary or P waves of strong aftershocks. Since the P waves travel at 5 km/sec maximum, and the damaging secondary or S waves follow at approximately 3 km/sec, a warning signal could be triggered at a building site prior to the damaging effects of the S wave. The device comes in a portable carrying case and would need to be bolted to a solid slab/foundation, etc. somewhere near a damaged building. For sites within 10 km of the aftershock origin, there would not be enough warning to be useful. For sites over 50 km away, there would be would be time to escape to cover etc. (7 plus seconds). A device of this type was used at a site after the Loma Prieta earthquake in 1989.

Aftershock Warning System

The U.S. Geological Survey (USGS) and others have discussed making an aftershock warning system available to US&R Task Forces during the first week after an earthquake. The system uses an array of sensors near the fault to detect aftershocks. A warning signal is relayed by repeaters to individual pagers that will be given to each task force involved in rescue operations. For sites that are about 10 km from the active fault, there will be only 3 seconds warning. For sites that are 50 km away, there will be 12 seconds warning (proportionally greater warning for greater distance from aftershock origin).

WIND SPEED MONITORS

Any monitoring operation must include the means to measure the wind speed. Regardless of what caused the initial damage to the structure, the lateral forces generated by wind pressures can cause movement or collapse to the hazard being monitored. It is crucial to the monitoring plan that the affect of wind be fully understood, both as a historical factor over the time of the rescue operation and as an alarm trigger prior to collapse. Various inexpensive pocket devices are available and are included in the FEMA US&R cache. More sophisticated wind meter systems may also be available during an event. Structures Specialist personnel must be acquainted with these devices and understand their limitations in order to properly utilize the data they provide.

MONITORING PLAN

Effective structural monitoring requires an established plan. Essential elements of that plan include:

- Objective: what is the failure mode of concern?
- Data collection: how can potential structural movement best be measured and recorded?
- Interpretation: what level of movement indicates impending collapse?
- Control/reference points: how can a monitoring station be reestablished in the event it must be moved or the line of site is somehow blocked during rescue operations?
- Communication: how are results of the monitoring to be conveyed to those who need to know?
- Proper documentation: how is the monitoring data recorded and transferred?
- Trained monitoring personnel: what happens if the one trained person performing the monitoring is called off to perform another task or becomes injured and can't continue monitoring?

Monitoring Objective

An effective monitoring plan requires a clear definition of purpose and understanding of the potential failure mode of concern. The purposes of the monitoring plan may be to provide advance warning of impending collapse or falling debris. To be effective, monitoring must provide enough warning to be detectable with available instrumentation and must provide that warning sufficiently in advance of collapse or falling debris to allow for sounding an alarm and evacuating the site. Effective monitoring also requires understanding the response of the structure to extreme loads such as aftershocks or high wind, and rescue activities such as debris removal and placement of heavy equipment. While there may be no evacuation protocol associated with this monitoring, such monitoring can provide insight into the stability (or lack thereof) of the structure under significant loading.

The potential failure mode must be well-defined and understood. Not all potential failure modes are amenable to effective monitoring. In general, ductile failure modes are good candidates for monitoring; brittle failure modes are not. Thus, racking of a soft story in a steel moment frame is an excellent candidate for monitoring; falling of unreinforced masonry debris is not. Failure modes amenable to effective monitoring include:

- Sideways racking of a story or structure
- Tilting of a structure
- Cantilever bending of a wall or column
- Flexure overload of beams and floor slabs
- Crushing of wedges supporting shoring
- Existing cracks in concrete

Failure modes not amenable to effective monitoring include:

- Shifting or sliding of an inclined debris pile
- Falling of hanging debris
- Shear failure of concrete slabs or beams
- Column buckling
- Collapse of unreinforced masonry walls during aftershocks
- Buckling of slender shores and rakers

Data Collection

Effective monitoring must be quantitative, with respect to both time and magnitude of movement, and must be documented systematically. Thus, means and methods must quantify and record data at regular intervals. Quantification of data may take the form of linear or angular displacement. One exception to strict quantification is monitoring of the condition of shoring wedges, where quantification may take the form of a qualitative description of the degree of crushing and cupping at each location, or photographs. Undocumented qualitative visual observations should not be used.

Depending on the instrumentation employed, story or building drifts may be measured linear offsets (e.g., if using a total station) or as angular movement (e.g., if using the WBMS or Smart level). Data should be recorded periodically, either electronically or on appropriate monitoring data sheets that can be passed along to the next shift as part of the hand-off process. There is much to be learned from the long-term trend of the data, and that information will be lost unless the data are recorded in a consistent fashion and that record is passed from one shift to the next.

Data should also be collected and recorded following significant events such as aftershocks, windstorms, shifting of debris, etc.

Data Interpretation

Interpretation of monitoring data is the most challenging aspect of structural monitoring. In a worst-case scenario, the Structures Specialist must extrapolate into the future from a limited set of measurements and make predictions about impending collapse of a damaged structure about which little is known of its ultimate capacity. Structural monitoring data must also be considered in the overall context of the structural condition of the building and the incident.

As every structural monitoring situation is unique, there are no simple rules for data interpretation. The key to data interpretation is observing and understanding patterns and trends. Key factors to consider are:

- Initial conditions
- Magnitude of movement
- Rate of movement
- Trend of movement: noise, cyclic, monotonic, ratcheting, or stepped

- External influences associated with observed movements

All movement must be considered in the context of the initial displaced or deformed conditions. While monitoring data generally record deviations from an initial zero reference, the actual structure may have an initial displacement of inches or feet from its as-built position. Incremental observed movement must be considered relative to the scale of the initial movement. One inch of movement in a structure 10 feet out of plumb will likely be of less concern than 1 inch of movement in a column that is 2 inches out of plumb. The magnitude of movement is the easiest and most common data to collect. Whether in inches or degrees, monitoring data will indicate how much the structure has moved from its initial conditions. For structures, such as a free-standing unreinforced masonry wall, the tolerable magnitude of movement is relatively easy to determine. Once the center of gravity of the wall moves outside the base of the wall, gravity will bring the wall down.

The rate of movement is as important, but less obvious than the magnitude of movement. While magnitude of movement will be recorded directly, the rate of movement will require some processing of the data, either recording the change over fixed time intervals or plotting the data as a function of time. Generally the rate of movement will increase as the structure becomes more unstable and approaches collapse.

Examining the trend of the data over time can provide insight into the behavior of the structure and monitoring equipment. Small, random oscillations about zero typically reflect “noise” in the monitoring equipment or the effect of minor external influences. The simplest example is the oscillation of a plumb bob in a light breeze.

More pronounced movements that fluctuate about zero over a longer period of time likely reflect structural movements associated with solar heating and cooling. An example of this movement was the circular concrete ventilator shaft of the Murrah Building in Oklahoma City which oscillated back and forth by approximately 5/8-inch during the course of the day as the sun moved around the shaft. Noise and cyclic movements are generally not of concern. In contrast, movements that increase monotonically indicate progressive deformation or movement and are cause for concern, especially if the rate of movement is increasing or approaching a point of collapse. Ratcheting is a combination of cyclic and monotonic movements. Ratcheting occurs when a structure deforms under a cyclic external influence, but does not return to its starting point when the external influence abates.

A step or abrupt change in movement can occur during an earthquake aftershock or equipment impact during debris removal. If the data remain stable following the step, there is generally no cause for concern, although the condition of physical mitigation measures should be checked. Note well that the most common cause of abrupt changes in data is the result of instrumentation being disturbed. External influences that influence structural behavior should be recorded, and quantified if possible. When correlated with monitoring data, the effect of wind, rain, aftershocks, solar heating, debris removal activities, etc., will provide insight into structural behavior and, in many cases, increase the level of understanding of the stability of the structure.

When interpreting monitoring data, it is essential to consider both elastic structural movements that may be caused by thermal cycling or wind loads as well as “noise” or measurement error. Estimates of elastic structural movement from normal environmental influences (wind and temperature) are as follows:

- Concrete structure: 1/16 inch per story (0.025 degree)
- Steel structure: 2/16 inch per story (0.05 degree)

- Wood structure: 3/16 inch per story (0.075 degree)

Note that these are rough estimates only. Elastic, environmental movements in any particular structure will depend on the type of lateral system (frame, braced frame, shear wall) and extent of damage to the structural system. Estimates of instrument noise are as follows:

- Plumb bob – for monitoring of horizontal movement, highly vulnerable to any wind, which will cause oscillations as well as a slight shift in the mean position of the tip. For vertical movement, vulnerable to change of length of string due to creep and temperature.
- Crack gauge – parallax can be an issue when reading the gauge, especially for small movements and multiple observers.
- Smart level – resolution of the smart level is 0.1 degree. Instrument noise of +/- 0.1 degree is common.
- Laser – resolution of a laser set-up is a function of the diameter of the beam on the target (which may change with battery strength). “Noise” in a laser set-up is a function of stiffness and stability of the mounting of the laser.
- Total station – resolution and “noise” in surveying instruments are dependent on instrument quality as well as stiffness and stability of the tripod set-up.
- Wireless Building Monitoring System – resolution of the WBMS is 0.01 degree, but, due to instrument noise, repeatable readings are no smaller than 0.05 degree.

Control/Reference Points

It is essential that any monitoring plan include a system for establishing of control and reference points to help ensure the accuracy of the monitoring. Control points should be visible in various conditions and from at least two monitoring locations (to observe movements in X, Y, and Z directions). Control points should be checked often in order to eliminate false reading. False reporting will destroy the credibility of the entire monitoring program.

Control points need to be selected for stability. The effect of the following need to be anticipated and understood:

- Wind and temperature
- Changes caused by debris removal
- Changes in sight lines

Communication Protocols

Alert thresholds and lines of communication between individual monitors and Incident Leadership must strike a balance between rapid notification of an impending collapse and avoidance of false alarms. Leadership should be informed when the structure moves beyond a pre-determined alert threshold. This level of movement should be greater than background or noise level movements but below the level at which collapse is of concern. Leadership should be informed that significant movement has been observed and monitoring staff should continuously monitor the structure for additional movement. If movement exceeds a pre-determined alarm threshold, evacuation should be signaled. Depending on the circumstances, it may be appropriate to verify the observation or consult amongst the Structures Specialist or other qualified personnel and Leadership before signaling an evacuation. Incident Leadership may be as simple as the Task Force Leader, but often would involve the Incident Support Team Leadership and/or the Local Incident Commander.

Movement tolerances should be established for both caution and alarm notifications. Caution levels might include movements that are out of the expected, but not large enough to warrant evacuation. Alarm levels would include movements that telegraph impending collapse and evacuating rescue personnel is appropriate. Expected movements due to thermal expansion/contraction should not initiate a caution notification.

Monitoring Documentation

It is important to note that even the most well-developed monitoring plans can lack credibility if proper documentation techniques are not followed. Often specific time intervals for monitoring a hazard will provide the Structures Specialist with a cyclic behavior of a monitored hazard. For example a steel structure may translate a specific distance as the temperature rises and falls through typical weather changes that occur during rescue operations. Wind or rescue operations may affect the movement of a tall unbraced masonry wall. Through proper documentation of hazard monitoring, these movements can be incorporated into the alert and/or alarm displacements. Evacuating a rescue operation site can be disruptive and in some cases more dangerous than working within a hazardous location. If a site is evacuated and a hazard does not collapse into the site, credibility of the monitoring plan can be questioned. If rescue personnel do not have faith in the monitoring plan, they may not evacuate or shelter in a hazardous location when a true secondary collapse occurs. By understanding typical or expected movement of a hazard and properly documenting that movement, disruptive false alerts and evacuation alarms can be minimized.

Trained Monitoring Personnel

Personnel that are adequately trained to implement the monitoring plan are critical to an effective plan. In most cases the Task Force Structures Specialists need to focus their attention on other tasks, such as assessment, providing aid to the rescue efforts, mitigation design, etc. A Structures Specialist may even need to leave the site as part of a Search and Recon Team. In past incidents, the Incident Support Team (IST) Structures Specialist has been able to provide monitoring support to the Task Forces.

Trained individuals from the U.S. Army Corps of Engineers will normally be available, as part of the IST staff, to provide monitoring as well as other support to individual Task Forces. Local, Professional Land Surveyors have also been used to augment the monitoring needs at a large incident. As a minimum, monitoring personnel should:

- Be thoroughly trained in the use of monitoring tools and equipment.
- Be able to translate observed conditions into appropriate action.
- Be able to detach themselves from the rescue operations for long periods of time.

CASE STUDIES

Monitoring has been used at many US&R events many times in the past. The following case studies present various circumstances where monitoring was used to provide warning to rescue crews working within a dangerous area. Note how each applies the basic tenets of monitoring;

analyzing the behavior of a ductile object, understanding the anticipated failure mode and establishing a criterion for alarm and action.

Case Study 1: Alfred P. Murrah Building, Oklahoma City, Oklahoma

At about 0900 local time on April 19, 1995 in Oklahoma City, Oklahoma, a truck exploded in front of the Alfred P. Murrah Building. The explosion nearly demolished the nine-story concrete structure, disintegrating columns and collapsing floors down atop one another. As a result of the explosion, a 35,000-pound block of concrete floor slab hung from the 9th floor of the badly damaged building (Figure 1).

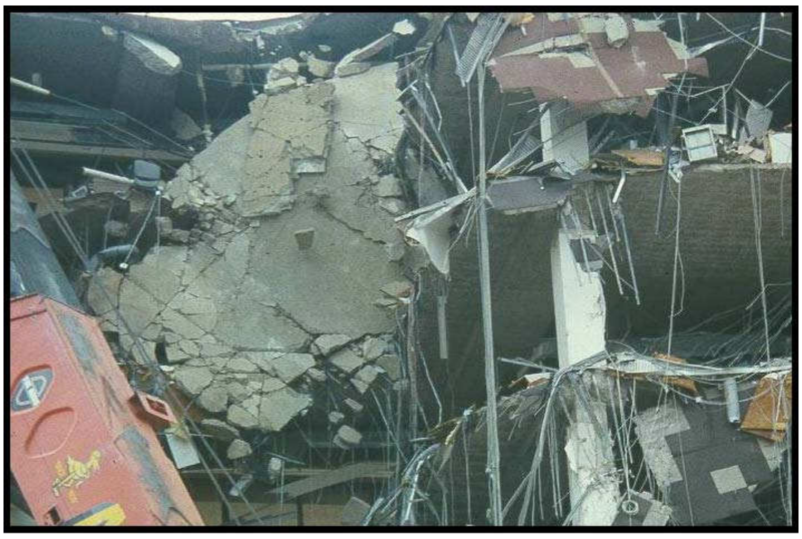

Figure 1: 35,000 pound concrete slab hanging from 9th floor of the Murrah Building, Oklahoma City, OK, April 1995

As rescue and recovery operations had to occur beneath the large falling hazard, decisions had to be made as to how to mitigate the risk to rescue personnel. After an unsuccessful attempt to remove the hazard, the decision was made to monitor the slab for movement. A warning alarm would be sounded if the slab was observed to shift more than a pre-established limit of displacement.

A theodolite was set up across from the site within a line of sight of the slab. The theodolite enabled a Structures Specialist to zoom in on a specific location and detect minute movement of the slab through a telescopic lens. The theodolite was manned around the clock whenever rescue and recovery operations were occurring.

Other points of the damaged building were monitored for movement using a theodolite instrument. These included the nearly free-standing corners of the damaged buildings as well as columns left with nearly four times the unbraced length as the column had been originally designed to support. These points were selected because they provided an overall picture of the stability of the structure.

Cyclic movement as a result of temperature, wind, and rescue operations was noted by the Structures Specialist and soon an anticipated pattern of behavior was established for the damaged structure. As operations moved from rescue to recovery, the monitoring of the hazards continued until the damaged building was completely demolished. Understanding the patterned movement enabled the Structures Specialist to provide confident assessment of the risk to rescue and recovery personnel.

Case Study 2: Worcester Cold Storage Bldg. Fire, Worcester, Massachusetts

At approximately 1815 local time on December 3, 1999, the Worcester Fire Department responded to a building fire at an abandoned cold storage warehouse (Figure 2). Arriving firefighters initiated interior operations to search for occupants and extinguish the fire. While engaged in these operations, a series of structural collapses occurred, trapping six firefighters in the building.

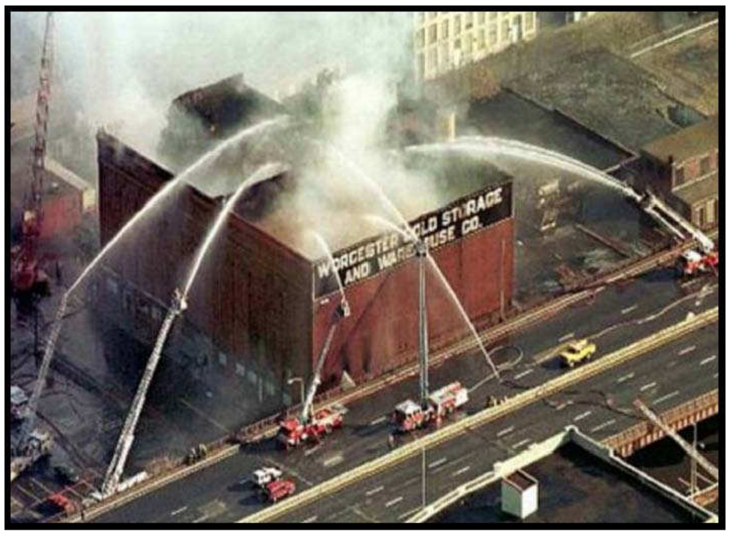

Figure 2: Unreinforced Masonry Walls of the Worcester Cold Storage Building During Fire on December 3, 1999, Worcester, MA

The building was still burning in many locations, and active fire suppression efforts were ongoing when structural engineers arrived on site. The Incident Commander requested an immediate structural assessment of the remaining building and recommendations on how best to breach the exterior walls to gain access to the interior of the building. Fire and smoke limited the ability of the structural engineers to determine the condition of the walls.

The structural engineers determined the six-story structure was divided into two sections separated by an unreinforced brick firewall. The structural framing system was heavy timber framing on cast iron columns, with unreinforced brick masonry exterior bearing walls. The second floor was a reinforced concrete slab on concrete encased steel beams.

The structural engineers recommended that the exterior wall be breached from the top midway along its length and progressing down in a V-shaped notch. The engineers also recommended that the walls be monitored using theodolites to permit remote observation of the walls. A schedule for monitoring the exterior walls during the demolition was established to minimize the risks associated with carrying on search and recovery activities in conjunction with the needed building demolition activities.

Four theodolite instruments were set up around the structure to facilitate monitoring of movement of the exterior walls. Anticipated movement as a result of wind loads was established and deflection limits were established using bonding strength of the unreinforced masonry. The instrument locations were selected such that the engineers would have early detection of movement and be able to alert rescuers working within the hazardous fall zone.

During operations it was determined that the location of one of the instruments was not optimum for determining the actual lateral movement of the wall as a result of wind. The angle of the instrument to the wall created an illusion of greater movement when sited by the engineer on the instrument. The structural engineers on site gathered to discuss the observations and quickly discovered the actual movement of the wall.

Monitoring of the walls during recovery operations continued until large movements of the wall was detected during 40 mph wind gusts. Although the wall continued to move back and forth approximately 2 inches at the top, the motion remained elastic. After a week of continuous observation of the walls, the final firefighter's remains were removed from the building and the operation ended.

Case Study 3: World Trade Center Building #5, New York, New York

Following the collapse of the World Trade Center Towers, the surrounding buildings that had sustained partial damage needed to be searched. On September 13, 2001, a structural engineer was tasked to detect movement of World Trade Center Building #5 while search operations were occurring. The structural engineer determined that the steel moment frame building would collapse in a slow ductile manner and developed a monitoring plan.

The nine-story steel frame building that comprised WTC #5 was located adjacent to the collapsed towers and suffered extensive damage as a result of falling debris and fire within the structure (Figure 3). A subway station was located beneath the structure with access to the station through the building. The underground area housed many restaurants and the largest Borders bookstore in New York City.

Figure 3: Steel Frame Building Following Collapse of the World Trade Center Towers, September 13, 2001 New York City, New York

A structural engineer established a monitoring plan and positioned a theodolite instrument to observe movement of a corner of the roof of structure. The engineer also determined what the limit of lateral displacement would be prior to sounding an evacuation alarm to cease recovery operations. The engineer was then called to another task and left the monitoring of the structure to another search and rescue team member familiar with the theodolite, but not as familiar with potential errors that could occur.

Typically an engineer monitoring a structure with a theodolite uses certain cues and procedures to ensure the observed data is accurate. Prior to sounding an alarm that a building has moved significantly, the engineer will quickly look at the level bubbles of the instrument and maybe sight a control point to ensure the instrument hasn't moved. These quick checks enable the engineer to accurately discern between structure and instrument movement.

When the engineer was called off to perform another task, the team member left to monitor the structure noted movement that appeared to be greater than the pre-established limit of expected displacement. Rather than double check the instrument or control point data, the team member sounded the evacuation alarm clearing rescuers from the building and surrounding area. Following the evacuation and a few awkward minutes of waiting, the engineer and the team member noted that the theodolite instrument had been moved slightly, providing a false displacement reading for the structure.

The example above emphasizes the training and experience that goes into monitoring a hazard during search and rescue operations. It also provides an example of how important full communication is and how the second team member was not fully educated of the methods to ensure accurate reporting of data.

SUMMARY

Monitoring is only effective for failure modes where collapse is preceded by slow, measurable deformation. Monitoring is not effective for failure modes where collapse is sudden and occurs with little or no measurable deformation. Effective monitoring must be quantitative, documented, and have an effective communication plan. Hazards of questionable stability as well as shoring, bracing, and restraining of mitigated hazards must be appropriately monitored. A monitoring plan must identify the failure mode(s) considered, the means and methods for collecting and recording monitoring data, criteria for interpreting the data (alert and alarm thresholds), and protocols for communication when and if movement exceeds established thresholds.

Power Point Presentations

Efforts of ASCE Regarding Building Stabilization after Abnormal Events

Amar Chaker

EFFORTS OF ASCE REGARDING BUILDING STABILIZATION AFTER ABNORMAL EVENTS

Amar Chaker, Ph.D.
Director, Architectural Engineering Institute
and Engineering Mechanics Institute of ASCE

DHS Workshop on Stabilization of Buildings, August 25-27, 2009 – Vicksburg, MS

WHAT IS STABILIZATION OF BUILDINGS?

- Role of Structural System:
  Transfer all loads to foundation soil, so that equilibrium is achieved
- This “normal” condition no longer exists and there is **incipient collapse** if:

  1- Members become unable to carry or transfer loads, mechanisms form, or instability appears

  and/or

  2- Support is no longer provided

EXAMPLES OF SITUATIONS WHERE COLLAPSE MAY BE INCIPIENT

1- Structural damage

- Failure of members (buckling, fracture, crushing, etc.)
- Damage to connections between members,
- formation of hinges and mechanisms
- Local or global instability

2- Absence of support

- Differential settlement
- Erosion
- Thawing of permafrost
- Soil liquefaction

ASCE’s MISSION

- Advance civil engineering knowledge
- Advance civil engineering practice
- Advance civil engineering profession

- Fundamental Canon # 1 of ASCE’s Code of Ethics:
  “Engineers hold paramount the safety, health and welfare of the public […]”

MULTIPLE VEHICLES TO CARRY OUT ASCE’s MISSION

- Dissemination of Information
  - Journals, monographs, manuals of practice, proceedings, committee reports and other publications
  - Conferences, workshops and symposia
  - Continuing education activities
- Advancing the Practice and the Profession
  - Development of standards (ANSI-accredited SDO)
  - Technical committees

Efforts of ASCE Regarding Building Stabilization after Abnormal Events

Amar Chaker

ASCE's EFFORTS

- 10,000 volunteers
- > 500 committees
- Effort of the **members and committees of ASCE** to address building stabilization
  - Numerous publications
  - Numerous events (conferences, workshops, symposia, short courses, etc.)
  - Numerous on-going committee activities

COMMITTEES – A SAMPLING FROM THE ASCE OFFICIAL REGISTER

- Editorial Board of *J. of Structural Engineering*
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- Editorial Board of *J. of Performance of Constructed Facilities*
- Technical Council on Forensic Engineering
- Technical Council on Lifelines Earthquake Engineering/ Earthquake Investigations Committee
- AEI Committee on the Mitigation of the Effects of Terrorism
- SEI ASCE 7 Committee
- SEI Committee on Structural Condition Assessment and Rehabilitation of Building Structures
- SEI Subcommittee on Structural Condition Assessment of Existing Buildings
- SEI Subcommittee on Structural Condition Assessment of Building Envelopes
- SEI Standards Committee on Blast Protection of Buildings
- SEI Committee on Blast, Shock and Impact
- SEI Committee on Design for Physical Security
- SEI Committee on Progressive Collapse Standards and Guidance
- SEI Reliability-Based Structural System Performance Indicators
- SEI Committee on Air supported Structures
- EMI Stability Committee
- Committee on Critical Infrastructure
- Building Security Council/ Rating System Development Committee

WHEN DO CIVIL ENGINEERS CONSIDER OR ENCOUNTER INCIPIENT COLLAPSE?

- During design (usual circumstances and extreme events)
- During phases of construction/erection
- When modifications are sought
- When designing a retrofit
- When evaluating the safety and reliability of a structure (e.g. vulnerability assessment)
- During efforts for historic preservation
- During post-disaster or forensic investigations to understand the causes of a collapse
- During Search and Rescue operations
- During demolition

PUBLICATIONS – A SAMPLING FROM THE ASCE RESEARCH LIBRARY

EVALUATING COLLAPSE SAFETY

Methods to Assess the Seismic Collapse Capacity of Building Structures: State of the Art

Roberto Villaverde, P.E., M.ASCE[1]

Abstract: The collapses of building structures during recent earthquakes have raised many questions regarding the adequacy of current seismic provisions to prevent a partial or total collapse. They have also brought up questions as to how to determine the collapse safety margin of structures, what is the inherent collapse safety margin in code-designed structures, and how to strengthen structures to effectively augment such margin. The purpose of this paper is to present a comprehensive review of the analytical methods that are currently available to assess the capacity of building structures to resist an earthquake collapse, point out the limitations of these methods, describe past experimental work in which specimens are tested to collapse, and identify what is required for an accurate evaluation of the seismic collapse capacity of a structure and the safety margin against such a collapse. It is contended that further research is needed before the collapse capacities of structures and their safety margin against collapse may be evaluated with confidence.

DOI: 10.1061/(ASCE)0733-9445(2007)133:1(57)

CE Database subject headings: Structural analysis; Structural failures; Earthquake engineering; Seismic analysis; Structural safety; Structural stability; Collapse.

Structures 2008: Crossing Borders © 2008 ASCE

ATC 63 Methodology for Evaluating Seismic Collapse Safety of Archetype Buildings

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OVERVIEW

This is one of four companion papers describing the Applied Technology Council project (ATC-63) to develop a methodology to assess seismic design provisions for building systems. This paper describes the underlying approach to evaluate the collapse safety of a set of archetype buildings, whose designs reflect the key features of the seismic design requirements. The companion papers provide a broader overview of the ATC 63 project [Kircher and Heintz, 2008] and two application studies to reinforced concrete moment frames [Haselton et al. 2008] and wood-frame buildings [Filiatrault et al. 2008]. Following an overview of the assessment methodology, this paper reviews specific aspects related to (a) modeling collapse assessment of buildings by nonlinear time-history analysis, (b) development of collapse fragility curves, including variability due to design, construction, and modeling uncertainties, (c) ground motion characteristics with adjustment for spectral shape effects for collapse assessment, (d) evaluation and acceptance criteria for archetype building models.

Efforts of ASCE Regarding Building Stabilization after Abnormal Events

Amar Chaker

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Experimental and analytical investigations on the response of structural building frames further to a column loss

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ABSTRACT

Recent events such as natural catastrophes or terrorism attacks have highlighted the necessity to ensure the structural integrity of buildings under exceptional events. Design requirements are proposed in some codes but are generally not satisfactory. In particular, it is not demonstrated that, even if these requirements are respected, a structure subjected to an exceptional event will really behave properly.

A European RFCS project called "Robust structures by joint ductility" has been set up in 2004, for three years, with the aim to provide requirements and practical guidelines so as to ensure the structural integrity of steel and composite structures under exceptional events through an appropriate robustness.

The investigations performed at the University of Liège, as part of this European project, are mainly dedicated to the exceptional event "loss of a column in a steel or steel-concrete composite building frame"; the main objective is to develop a simplified analytical procedure to predict the frame response further to a column loss. The development of this simplified procedure is detailed in two complementary PhD theses: the thesis of Demonceau J.-F. and the thesis of Luu N.N.H. Present paper describes experimental and analytical studies carried out in [Demonceau, 2008]. In particular, a simplified analytical procedure for the prediction of the global frame response when significant membrane forces develop further to a column loss will be described; it allows: (i) to predict the development of the catenary action in a frame with joints subjected to combined bending moment and tension loads and (ii) to compute the requested rotation capacity at the joint level according to the loads applied on the frame.

Measures of Structural Robustness – Requirements & Applications

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INTRODUCTION

The investigation of structures concerning their susceptibility to progressive disproportionate collapse is attracting increasing attention. At present, there is neither a uniform theory of progressive collapse and collapse resistance nor any agreement on terms and nomenclature. Codes and other relevant literature require a reduction in the susceptibility to progressive collapse. However, mainly qualitative and hardly any quantitative recommendations are provided.

Collapse resistance can be influenced in various ways. One possibility is through the structural robustness. In a robust structure, no damage disproportionate to the initial failure will occur. To examine a structure in terms of its robustness, a quantitative description of the robustness by means of a measure would be useful.

In this work, basics for the development of measures to quantify structural robustness are formulated. Essential definitions are suggested and the requirements for measures of robustness as well as possible applications are discussed. A selection of publications on the quantification of robustness, or related characteristics such as vulnerability, are presented and discussed regarding the proposed requirements and applications.

Overview of Simplified Methods and Research for Blast Analysis

Mr. Douglas Sunshine[1], Dr. Ali Amini[2], and Mr. Mark Swanson[3]

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[2] Structural Engineer, Defense Threat Reduction Agency (DTRA), 8725 John J. Kingman Road, Mail Stop 6201, Ft. Belvoir, VA 22060-6201; PH (703) 325-1165; FAX (703) 325-1327; email: Ali.Amini@dtra.mil
[3] Engineer, Northrop Grumman, Threat Reduction Technology Division, 6940 South Kingshighway, Alexandria, VA 22310; PH (703) 971-3108; FAX (703) 971-4654; email: Mark.Swanson@ngc.com

Abstract

Recent terrorist bomb attacks on buildings have resulted in increased interest in the protection of key buildings. Various research programs have provided improved design and analysis techniques as well as new mitigation methods. Advanced finite element methods provide the best analytical results because they can take into account the time varying load, dynamic structural response, non-liner material properties, and the non-linear interaction of various response modes (e.g., shear and flexure). These methods require not only time but also specialized expertise to obtain good results. They are therefore generally unpractical for typical blast design problems. Simplified methods can provide reasonable approximations that are adequate for design. A variety of types of simplified models exist. Typical models include single or multi-degree-of-freedom, pressure-impulse (P-I) diagrams, and response surfaces developed from finite element analyses. This paper describes some recently developed simplified models and associated research.

DEVELOPMENT OF AN ANALYTICAL DATABASE TO SUPPORT A FAST RUNNING PROGRESSIVE COLLAPSE ASSESSMENT TOOL

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Abstract

Rapid assessment of structures for vulnerability to progressive collapse has become a major concern in today's world environment. Homeland Security and Overseas U. S. government agencies need the ability to quickly, and realistically, evaluate buildings to determine the risk of progressive collapse and understand how proposed retrofits would improve the building risk.

To support the development of a fast running assessment tool, a series of simplified finite element simulations were conducted to generate a response data base. Models of simplified concrete and steel frames were run under gravity collapse conditions to determine displacements, forces and moments transmitted to adjacent structural members. The simulations were performed using Weidlinger Associates' FLEX finite element code.

This paper will discuss the salient issues involved in the nonlinear, dynamic modeling of progressive collapse. The FLEX modeling used to develop the data base and confirm expected response is also described in detail. Finally, the simplified analytical tool that was developed from the simulation data base development effort will be described.

DURING ERECTION OR CONSTRUCTION

COLLAPSE OF METAL BUILDING SYSTEM DURING ERECTION

By Thomas Sputo[1] and Duane S. Ellifritt,[2] Members, ASCE

ABSTRACT: Metal building systems are a common method of providing covered, enclosed space quickly at a competitive cost. Because of the system design approach, all components of the structure interact with each other to provide the required level of structural safety. Metal building systems are most vulnerable to collapse during erection, when all components are not yet installed. It is most important at this time to ensure that all bracing called for by the building manufacturer is properly installed. This paper reports on the collapse of a metal building system consisting of a 206 ft (62.8 m) span rigid frame during erection due to inadequately installed bracing, and explains proper erection procedure with regard to lateral bracing of the rigid frames. The circumstances of the collapse are discussed and recommendations are provided.

FIG. 2. Collapsed Rigid Frames

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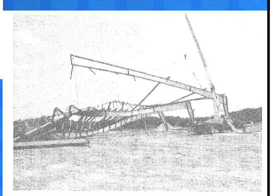

FIG. 4. Partially Erected Third Rigid Frame

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Efforts of ASCE Regarding Building Stabilization after Abnormal Events

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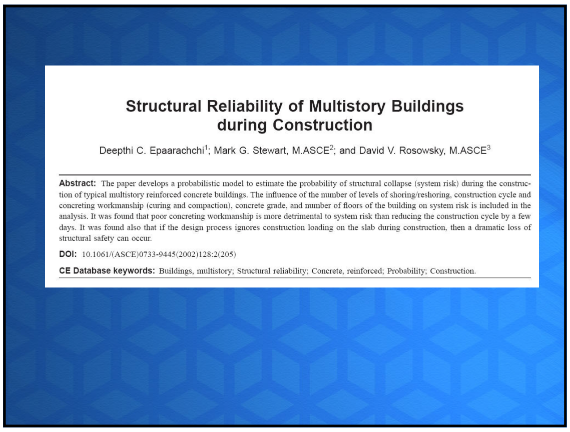


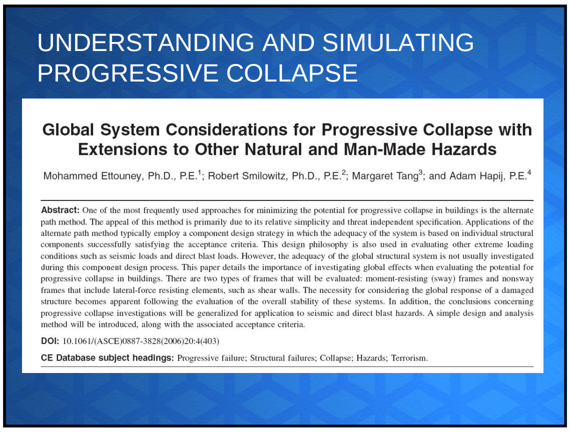
Structural Reliability of Multistory Buildings during Construction

Deepthi C. Epaarachchi[1]; Mark G. Stewart, M.ASCE[2]; and David V. Rosowsky, M.ASCE[3]

Abstract: The paper develops a probabilistic model to estimate the probability of structural collapse (system risk) during the construction of typical multistory reinforced concrete buildings. The influence of the number of levels of shoring/reshoring, construction cycle and concreting workmanship (curing and compaction), concrete grade, and number of floors of the building on system risk is included in the analysis. It was found that poor concreting workmanship is more detrimental to system risk than reducing the construction cycle by a few days. It was found also that if the design process ignores construction loading on the slab during construction, then a dramatic loss of structural safety can occur.

DOI: 10.1061/(ASCE)0733-9445(2002)128:2(205)

CE Database keywords: Buildings, multistory; Structural reliability; Concrete, reinforced; Probability; Construction.



UNDERSTANDING AND SIMULATING PROGRESSIVE COLLAPSE

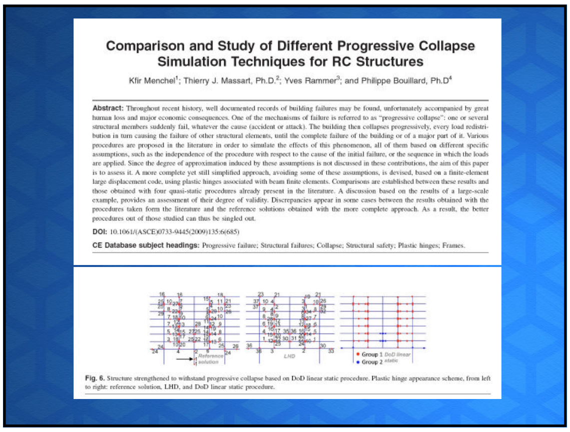
Global System Considerations for Progressive Collapse with Extensions to Other Natural and Man-Made Hazards

Mohammed Ettouney, Ph.D., P.E.[1]; Robert Smilowitz, Ph.D., P.E.[2]; Margaret Tang[3]; and Adam Hapij, P.E.[4]

Abstract: One of the most frequently used approaches for minimizing the potential for progressive collapse in buildings is the alternate path method. The appeal of this method is primarily due to its relative simplicity and threat independent specification. Applications of the alternate path method typically employ a component design strategy in which the adequacy of the system is based on individual structural components successfully satisfying the acceptance criteria. This design philosophy is also used in evaluating other extreme loading conditions such as seismic loads and direct blast loads. However, the adequacy of the global structural system is not usually investigated during this component design process. This paper details the importance of investigating global effects when evaluating the potential for progressive collapse in buildings. There are two types of frames that will be evaluated: moment-resisting (sway) frames and nonsway frames that include lateral-force resisting elements, such as shear walls. The necessity for considering the global response of a damaged structure becomes apparent following the evaluation of the overall stability of these systems. In addition, the conclusions concerning progressive collapse investigations will be generalized for application to seismic and direct blast hazards. A simple design and analysis method will be introduced, along with the associated acceptance criteria.

DOI: 10.1061/(ASCE)0887-3828(2006)20:4(403)

CE Database subject headings: Progressive failure; Structural failures; Collapse; Hazards; Terrorism.



Comparison and Study of Different Progressive Collapse Simulation Techniques for RC Structures

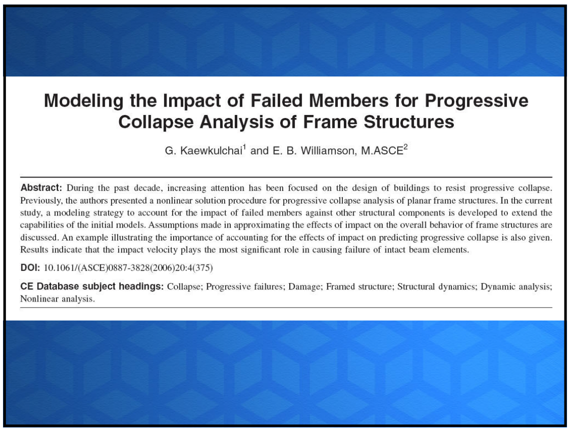
Kfir Menchel[1]; Thierry J. Massart, Ph.D.[2]; Yves Rammer[3]; and Philippe Bouillard, Ph.D[4]

Abstract: Throughout recent history, well documented records of building failures may be found, unfortunately accompanied by great human loss and major economic consequences. One of the mechanisms of failure is referred to as "progressive collapse": one or several structural members suddenly fail, whatever the cause (accident or attack). The building then collapses progressively, every load redistribution in turn causing the failure of other structural elements, until the complete failure of the building or of a major part of it. Various procedures are proposed in the literature in order to simulate the effects of this phenomenon, all of them based on different specific assumptions, such as the independence of the procedure with respect to the cause of the initial failure, or the sequence in which the loads are applied. Since the degree of approximation induced by these assumptions is not discussed in these contributions, the aim of this paper is to assess it. A more complete yet still simplified approach, avoiding some of these assumptions, is devised, based on a finite-element large displacement code, using plastic hinges associated with beam finite elements. Comparisons are established between these results and those obtained with four quasi-static procedures already present in the literature. A discussion based on the results of a large-scale example, provides an assessment of their degree of validity. Discrepancies appear in some cases between the results obtained with the procedures taken form the literature and the reference solutions obtained with the more complete approach. As a result, the better procedures out of those studied can thus be singled out.

DOI: 10.1061/(ASCE)0733-9445(2009)135:6(685)

CE Database subject headings: Progressive failure; Structural failures; Collapse; Structural safety; Plastic hinges; Frames.

Fig. 6. Structure strengthened to withstand progressive collapse based on DoD linear static procedure. Plastic hinge appearance scheme, from left to right: reference solution, LHD, and DoD linear static procedure.



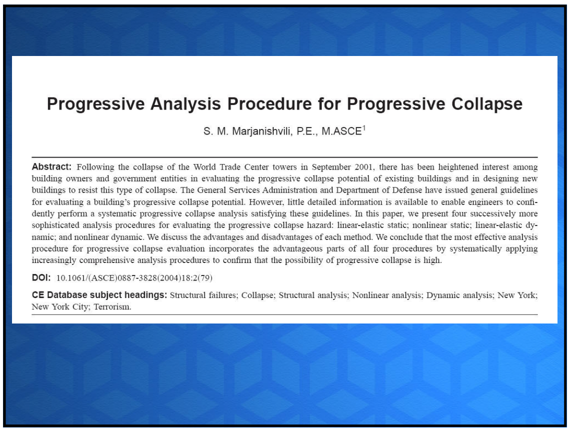
Modeling the Impact of Failed Members for Progressive Collapse Analysis of Frame Structures

G. Kaewkulchai[1] and E. B. Williamson, M.ASCE[2]

Abstract: During the past decade, increasing attention has been focused on the design of buildings to resist progressive collapse. Previously, the authors presented a nonlinear solution procedure for progressive collapse analysis of planar frame structures. In the current study, a modeling strategy to account for the impact of failed members against other structural components is developed to extend the capabilities of the initial models. Assumptions made in approximating the effects of impact on the overall behavior of frame structures are discussed. An example illustrating the importance of accounting for the effects of impact on predicting progressive collapse is also given. Results indicate that the impact velocity plays the most significant role in causing failure of intact beam elements.

DOI: 10.1061/(ASCE)0887-3828(2006)20:4(375)

CE Database subject headings: Collapse; Progressive failures; Damage; Framed structure; Structural dynamics; Dynamic analysis; Nonlinear analysis.



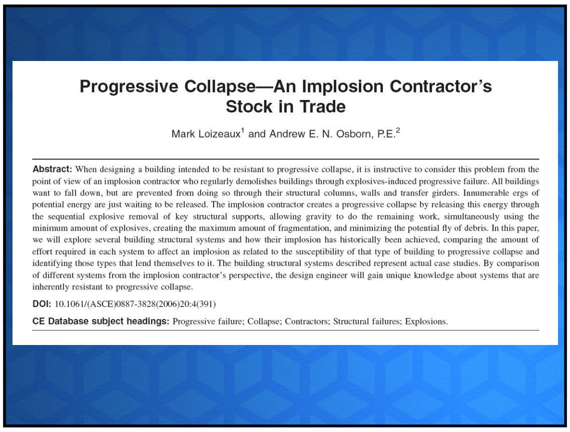
Progressive Analysis Procedure for Progressive Collapse

S. M. Marjanishvili, P.E., M.ASCE[1]

Abstract: Following the collapse of the World Trade Center towers in September 2001, there has been heightened interest among building owners and government entities in evaluating the progressive collapse potential of existing buildings and in designing new buildings to resist this type of collapse. The General Services Administration and Department of Defense have issued general guidelines for evaluating a building's progressive collapse potential. However, little detailed information is available to enable engineers to confidently perform a systematic progressive collapse analysis satisfying these guidelines. In this paper, we present four successively more sophisticated analysis procedures for evaluating the progressive collapse hazard: linear-elastic static; nonlinear static; linear-elastic dynamic; and nonlinear dynamic. We discuss the advantages and disadvantages of each method. We conclude that the most effective analysis procedure for progressive collapse evaluation incorporates the advantageous parts of all four procedures by systematically applying increasingly comprehensive analysis procedures to confirm that the possibility of progressive collapse is high.

DOI: 10.1061/(ASCE)0887-3828(2004)18:2(79)

CE Database subject headings: Structural failures; Collapse; Structural analysis; Nonlinear analysis; Dynamic analysis; New York; New York City; Terrorism.



Progressive Collapse—An Implosion Contractor's Stock in Trade

Mark Loizeaux[1] and Andrew E. N. Osborn, P.E.[2]

Abstract: When designing a building intended to be resistant to progressive collapse, it is instructive to consider this problem from the point of view of an implosion contractor who regularly demolishes buildings through explosives-induced progressive failure. All buildings want to fall down, but are prevented from doing so through their structural columns, walls and transfer girders. Innumerable ergs of potential energy are just waiting to be released. The implosion contractor creates a progressive collapse by releasing this energy through the sequential explosive removal of key structural supports, allowing gravity to do the remaining work, simultaneously using the minimum amount of explosives, creating the maximum amount of fragmentation, and minimizing the potential fly of debris. In this paper, we will explore several building structural systems and how their implosion has historically been achieved, comparing the amount of effort required in each system to affect an implosion as related to the susceptibility of that type of building to progressive collapse and identifying those types that lend themselves to it. The building structural systems described represent actual case studies. By comparison of different systems from the implosion contractor's perspective, the design engineer will gain unique knowledge about systems that are inherently resistant to progressive collapse.

DOI: 10.1061/(ASCE)0887-3828(2006)20:4(391)

CE Database subject headings: Progressive failure; Collapse; Contractors; Structural failures; Explosions.

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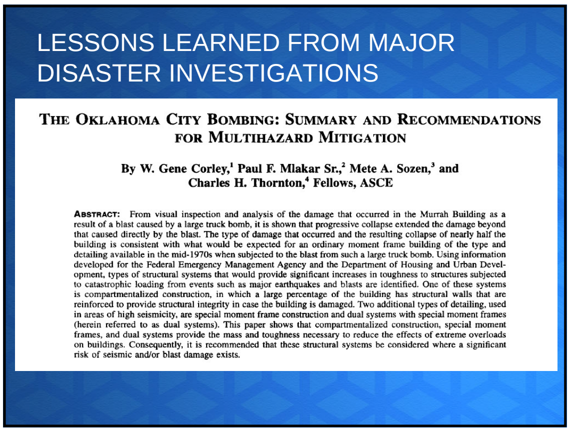
Amar Chaker

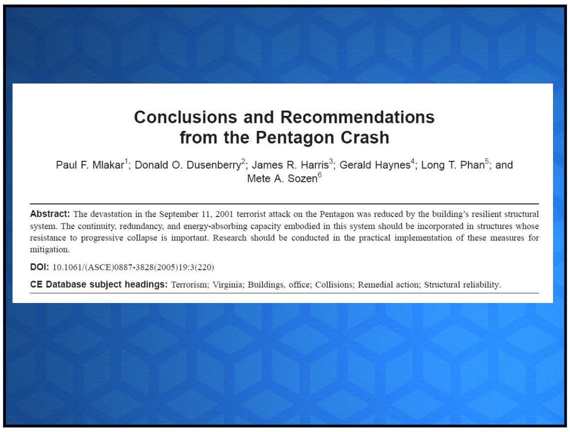


LESSONS LEARNED FROM MAJOR DISASTER INVESTIGATIONS

THE OKLAHOMA CITY BOMBING: SUMMARY AND RECOMMENDATIONS FOR MULTIHAZARD MITIGATION

By W. Gene Corley,[1] Paul F. Mlakar Sr.,[2] Mete A. Sozen,[3] and Charles H. Thornton,[4] Fellows, ASCE

ABSTRACT: From visual inspection and analysis of the damage that occurred in the Murrah Building as a result of a blast caused by a large truck bomb, it is shown that progressive collapse extended the damage beyond that caused directly by the blast. The type of damage that occurred and the resulting collapse of nearly half the building is consistent with what would be expected for an ordinary moment frame building of the type and detailing available in the mid-1970s when subjected to the blast from such a large truck bomb. Using information developed for the Federal Emergency Management Agency and the Department of Housing and Urban Development, types of structural systems that would provide significant increases in toughness to structures subjected to catastrophic loading from events such as major earthquakes and blasts are identified. One of these systems is compartmentalized construction, in which a large percentage of the building has structural walls that are reinforced to provide structural integrity in case the building is damaged. Two additional types of detailing, used in areas of high seismicity, are special moment frame construction and dual systems with special moment frames (herein referred to as dual systems). This paper shows that compartmentalized construction, special moment frames, and dual systems provide the mass and toughness necessary to reduce the effects of extreme overloads on buildings. Consequently, it is recommended that these structural systems be considered where a significant risk of seismic and/or blast damage exists.



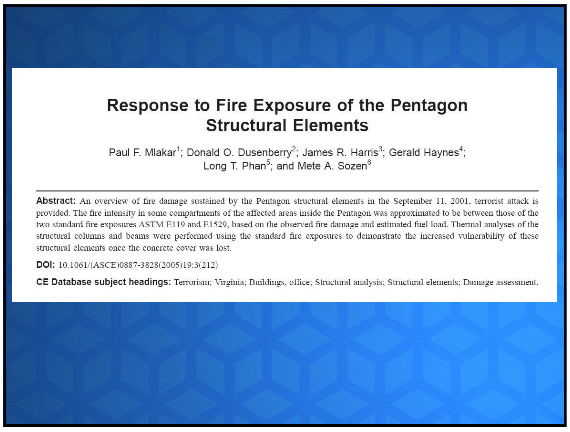
Conclusions and Recommendations from the Pentagon Crash

Paul F. Mlakar[1]; Donald O. Dusenberry[2]; James R. Harris[3]; Gerald Haynes[4]; Long T. Phan[5]; and Mete A. Sozen[6]

Abstract: The devastation in the September 11, 2001 terrorist attack on the Pentagon was reduced by the building's resilient structural system. The continuity, redundancy, and energy-absorbing capacity embodied in this system should be incorporated in structures whose resistance to progressive collapse is important. Research should be conducted in the practical implementation of these measures for mitigation.

DOI: 10.1061/(ASCE)0887-3828(2005)19:3(220)

CE Database subject headings: Terrorism; Virginia; Buildings, office; Collisions; Remedial action; Structural reliability.



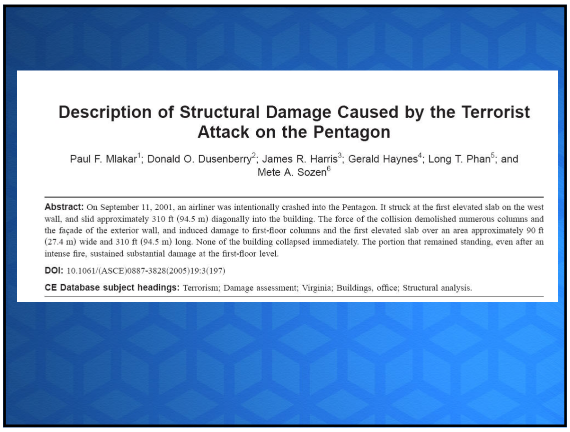
Response to Fire Exposure of the Pentagon Structural Elements

Paul F. Mlakar[1]; Donald O. Dusenberry[2]; James R. Harris[3]; Gerald Haynes[4]; Long T. Phan[5]; and Mete A. Sozen[6]

Abstract: An overview of fire damage sustained by the Pentagon structural elements in the September 11, 2001, terrorist attack is provided. The fire intensity in some compartments of the affected areas inside the Pentagon was approximated to be between those of the two standard fire exposures ASTM E119 and E1529, based on the observed fire damage and estimated fuel load. Thermal analyses of the structural columns and beams were performed using the standard fire exposures to demonstrate the increased vulnerability of these structural elements once the concrete cover was lost.

DOI: 10.1061/(ASCE)0887-3828(2005)19:3(212)

CE Database subject headings: Terrorism; Virginia; Buildings, office; Structural analysis; Structural elements; Damage assessment.



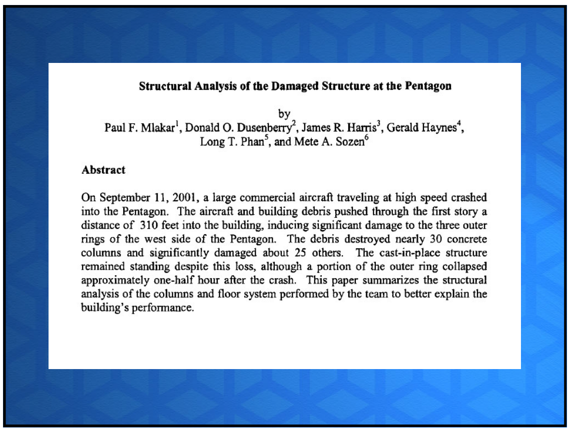
Description of Structural Damage Caused by the Terrorist Attack on the Pentagon

Paul F. Mlakar[1]; Donald O. Dusenberry[2]; James R. Harris[3]; Gerald Haynes[4]; Long T. Phan[5]; and Mete A. Sozen[6]

Abstract: On September 11, 2001, an airliner was intentionally crashed into the Pentagon. It struck at the first elevated slab on the west wall, and slid approximately 310 ft (94.5 m) diagonally into the building. The force of the collision demolished numerous columns and the façade of the exterior wall, and induced damage to first-floor columns and the first elevated slab over an area approximately 90 ft (27.4 m) wide and 310 ft (94.5 m) long. None of the building collapsed immediately. The portion that remained standing, even after an intense fire, sustained substantial damage at the first-floor level.

DOI: 10.1061/(ASCE)0887-3828(2005)19:3(197)

CE Database subject headings: Terrorism; Damage assessment; Virginia; Buildings, office; Structural analysis.



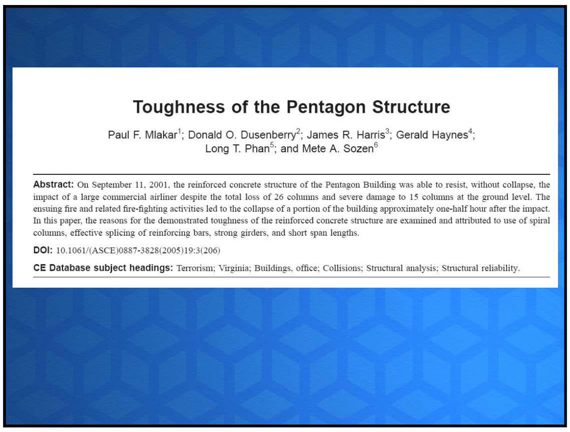
Structural Analysis of the Damaged Structure at the Pentagon

by

Paul F. Mlakar[1], Donald O. Dusenberry[2], James R. Harris[3], Gerald Haynes[4], Long T. Phan[5], and Mete A. Sozen[6]

Abstract

On September 11, 2001, a large commercial aircraft traveling at high speed crashed into the Pentagon. The aircraft and building debris pushed through the first story a distance of 310 feet into the building, inducing significant damage to the three outer rings of the west side of the Pentagon. The debris destroyed nearly 30 concrete columns and significantly damaged about 25 others. The cast-in-place structure remained standing despite this loss, although a portion of the outer ring collapsed approximately one-half hour after the crash. This paper summarizes the structural analysis of the columns and floor system performed by the team to better explain the building's performance.



Toughness of the Pentagon Structure

Paul F. Mlakar[1]; Donald O. Dusenberry[2]; James R. Harris[3]; Gerald Haynes[4]; Long T. Phan[5]; and Mete A. Sozen[6]

Abstract: On September 11, 2001, the reinforced concrete structure of the Pentagon Building was able to resist, without collapse, the impact of a large commercial airliner despite the total loss of 26 columns and severe damage to 15 columns at the ground level. The ensuing fire and related fire-fighting activities led to the collapse of a portion of the building approximately one-half hour after the impact. In this paper, the reasons for the demonstrated toughness of the reinforced concrete structure are examined and attributed to use of spiral columns, effective splicing of reinforcing bars, strong girders, and short span lengths.

DOI: 10.1061/(ASCE)0887-3828(2005)19:3(206)

CE Database subject headings: Terrorism; Virginia; Buildings, office; Collisions; Structural analysis; Structural reliability.

Lessons Learned on Improving Resistance of Buildings to Terrorist Attacks

W. Gene Corley, P.E., F.ASCE[1]

Abstract: This paper presents some findings of the FEMA and SEI/ASCE sponsored studies of structural performance of New York's World Trade Center (WTC) following the attacks of September 11, 2001, and the Murrah Building following the April 19, 1995, Oklahoma City bombing. The WTC collapses were caused not by aircraft impact alone but by the combination of impact and the resulting fire that weakened structural members and connections. On the other hand, the Murrah Building collapsed as a direct result of the blast. Although these studies call for further research in a number of areas, this report summarizes some of the lessons learned.

DOI: 10.1061/(ASCE)0887-3828(2004)18:2(68)

CE Database subject headings: Structural reliability; New York; New York City; Terrorism; Collapse; Oklahoma; Blasting; Explosion.

Mechanics of Progressive Collapse: Learning from World Trade Center and Building Demolitions

Zdeněk P. Bažant, F.ASCE[1]; and Mathieu Verdure[2]

Abstract: Progressive collapse is a failure mode of great concern for tall buildings, and is also typical of building demolitions. The most infamous paradigm is the collapse of the World Trade Center towers. After reviewing the mechanics of their collapse, the motion during the crushing of one floor (or group of floors) and its energetics are analyzed, and a dynamic one-dimensional continuum model of progressive collapse is developed. Rather than using classical homogenization, it is found more effective to characterize the continuum by an energetically equivalent snap-through. The collapse, in which two phases—crush-down followed by crush-up—must be distinguished, is described in each phase by a nonlinear second-order differential equation for the propagation of the crushing front of a compacted block of accreting mass. Expressions for consistent energy potentials are formulated and an exact analytical solution of a special case is given. It is shown that progressive collapse will be triggered if the total (internal) energy loss during the crushing of one story (equal to the energy dissipated by the complete crushing and compaction of one story, minus the loss of gravity potential during the crushing of that story) exceeds the kinetic energy impacted to that story. Regardless of the load capacity of the columns, there is no way to deny the inevitability of progressive collapse driven by gravity *alone* if this criterion is satisfied (for the World Trade Center it is satisfied with an order-of-magnitude margin). The parameters are the compaction ratio of a crushed story, the fracture of mass ejected outside the tower perimeter, and the energy dissipation per unit height. The last is the most important, yet the hardest to predict theoretically. It is argued that, using inverse analysis, one could identify these parameters from a precise record of the motion of floors of a collapsing building. Due to a shroud of dust and smoke, the videos of the World Trade Center are only of limited use. It is proposed to obtain such records by monitoring (with millisecond accuracy) the precise time history of displacements in different modes of building demolitions. The monitoring could be accomplished by real-time telemetry from sacrificial accelerometers, or by high-speed optical camera. The resulting information on energy absorption capability would be valuable for the rating of various structural systems and for inferring their collapse mode under extreme fire, internal explosion, external blast, impact or other kinds of terrorist attack, as well as earthquake and foundation movements.

DOI: 10.1061/(ASCE)0733-9399(2007)133:3(308)

CE Database subject headings: Buildings, high-rise; Progressive collapse; Demolition; New York; Terrorism; Failure; Fracture; Structural dynamics; Energy methods.

What Did and Did Not Cause Collapse of World Trade Center Twin Towers in New York?

Zdeněk P. Bažant, Hon.M.ASCE[1]; Jia-Liang Le[2]; Frank R. Greening[3]; and David B. Benson[4]

Abstract: Previous analysis of progressive collapse showed that gravity alone suffices to explain the overall collapse of the World Trade Center Towers. However, it remains to be determined whether the recent allegations of controlled demolition have any scientific merit. The present analysis proves that they do not. The video record available for the first few seconds of collapse is shown to agree with the motion history calculated from the differential equation of progressive collapse but, despite uncertain values of some parameters, it is totally out of range of the free fall hypothesis, on which these allegations rest. It is shown that the observed size range (0.01–0.1 mm) of the dust particles of pulverized concrete is consistent with the theory of comminution caused by impact, and that less than 10% of the total gravitational energy, converted to kinetic energy, sufficed to produce this dust (whereas, more than 150 t of TNT per tower would have to be installed, into many small holes drilled into concrete, to produce the same pulverization). The air ejected from the building by gravitational collapse must have attained, near the ground, the speed of almost 500 miles per hour (or 223 m/s, or 803 km/h) on average, and fluctuations must have reached the speed of sound. This explains the loud booms and wide spreading of pulverized concrete and other fragments, and shows that the lower margin of the dust cloud could not have coincided with the crushing front. The resisting upward forces due to pulverization and to ejection of air, dust, and solid fragments, neglected in previous studies, are indeed found to be negligible during the first few seconds of collapse but not insignificant near the end of crush-down. The calculated crush-down duration is found to match a logical interpretation of seismic record, while the free fall duration grossly disagrees with this record.

DOI: 10.1061/(ASCE)0733-9399(2008)134:10(892)

CE Database subject headings: Collapse; Structural dynamics; Buildings, high-rise; Towers; New York; New York City; Terrorism.

RETROFIT (BLAST)

Cost Effective Retrofit of Structures against the Effects of Terrorist Attacks – the Israeli Experience

R. Eytan

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Abstract

The paper includes the description of the extensive Israeli practical experience in developing and implementing protective measures to strengthen existing structures.

Much has been done recently to devise and implement protective hardening measures in new structures, such as preventing progressive collapse, minimizing the debris hazards, etc. However, much less has been done to strengthen existing structures, as this is considerably more difficult and more expensive, if at all feasible.

As Israel has been constantly subjected to terrorist attacks for decades, a vast practical experience has been gathered from the observed damages to structures from real-life terrorist attacks. Learning from the effects of terrorist attacks on actual buildings, considerable efforts were made in Israel to develop cost effective and easy-to-implement retrofit protective hardening measures.

Examples of various types of protective hardening measures implemented in existing structures are presented, as well as the SEPHRA (SEcurity Protection and Hardening Risk Analysis), developed by the author, resulting in the definition of the optimal cost effective protective retrofit measures.

Figure 3 – Energy absorbing catching cables during construction

The 2009 Joint ASCE-ASME-SES Conference on Mechanics and Materials — 2009 Joint Conference on Mechanics and Materials — June 24 - 27, 2009

Numerical Study of Energy Absorption Properties of Composite Sandwich Panels under Blast Loading

Miss HONG SU & Dr. Jennifer Righman McConnell

As blast threats on military and civilian structures continue to be a significant concern, there remains a need for improved design strategies for effectively mitigating these force effects. Composite sandwich panels are one such member type with promising applications to blast resistant structures due to their high stiffness-to-weight, high strength-to-weight and high energy-absorption-to-weight ratios. For this reason, the first objective of this research is to investigate the influence of the structural geometry on the energy absorption characteristics (which is used as a measure of blast resistance) of square-celled honeycomb sandwich panels. The influence of variations in dynamic loading are then explored through varying standoff distance. The sandwich panels considered are comprised of woven S2-glass/SC-15 epoxy.

In order to meet these objectives, an explicit dynamic finite element program LS-DYNA is used to model the panels subjected to blast loading. The structure was meshed using brick elements with single integration points. A progressive failure model, MAT_COMPOSITE_DMG_MSC, was employed to model failure of the material, while the panel was designed using. CONTACT_ERODING NODES TO SURFACE, which allows the contact with the remaining interior elements to continue when the exterior elements experience material failure.

Two suites of parametric study were carried out to examine the influence of (1) structural geometry and (2) dynamic loading (expressed here through variations in standoff distance of the charge center) on the relative energy absorption capability of the panel under blast loading. Relative energy absorption is defined as the energy absorbed by the core relative to the total energy absorbed by the panel. This evaluation criterion is selected because the design philosophy used in this work is that progressive collapse of the core of the sandwich panels is the desired means of energy absorption, while the face

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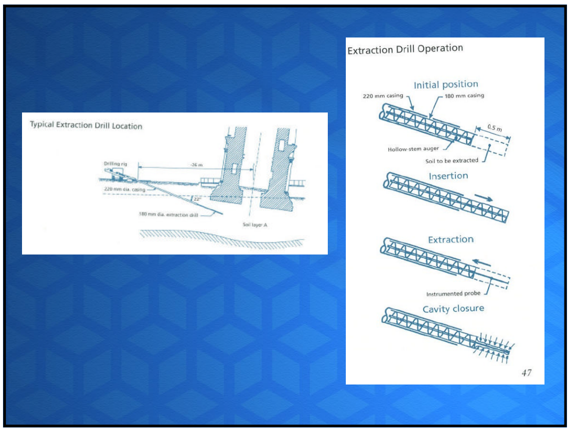
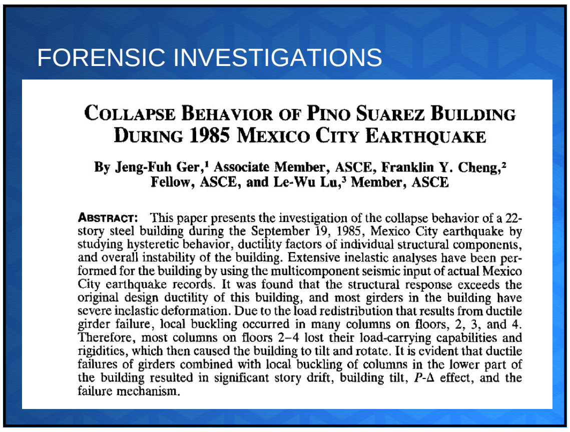
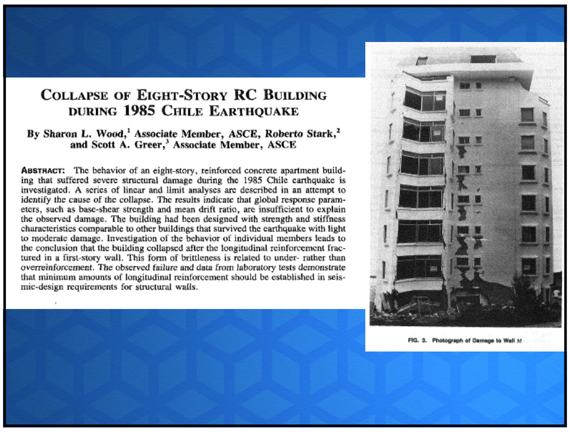




COLLAPSE BEHAVIOR OF PINO SUAREZ BUILDING DURING 1985 MEXICO CITY EARTHQUAKE

By Jeng-Fuh Ger,[1] Associate Member, ASCE, Franklin Y. Cheng,[2] Fellow, ASCE, and Le-Wu Lu,[3] Member, ASCE

ABSTRACT: This paper presents the investigation of the collapse behavior of a 22-story steel building during the September 19, 1985, Mexico City earthquake by studying hysteretic behavior, ductility factors of individual structural components, and overall instability of the building. Extensive inelastic analyses have been performed for the building by using the multicomponent seismic input of actual Mexico City earthquake records. It was found that the structural response exceeds the original design ductility of this building, and most girders in the building have severe inelastic deformation. Due to the load redistribution that results from ductile girder failure, local buckling occurred in many columns on floors, 2, 3, and 4. Therefore, most columns on floors 2–4 lost their load-carrying capabilities and rigidities, which then caused the building to tilt and rotate. It is evident that ductile failures of girders combined with local buckling of columns in the lower part of the building resulted in significant story drift, building tilt, P-Δ effect, and the failure mechanism.

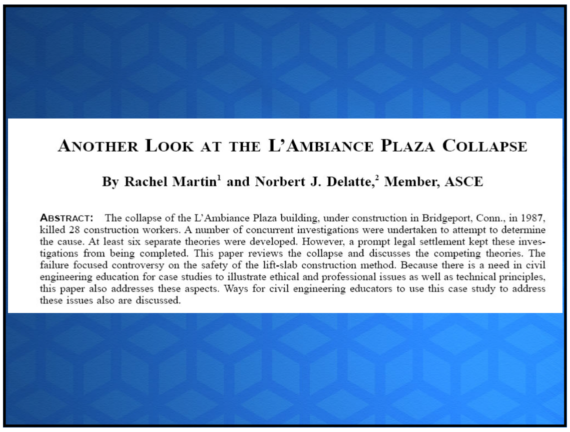


COLLAPSE OF EIGHT-STORY RC BUILDING DURING 1985 CHILE EARTHQUAKE

By Sharon L. Wood,[1] Associate Member, ASCE, Roberto Stark,[2] and Scott A. Greer,[3] Associate Member, ASCE

ABSTRACT: The behavior of an eight-story, reinforced concrete apartment building that suffered severe structural damage during the 1985 Chile earthquake is investigated. A series of linear and limit analyses are described in an attempt to identify the cause of the collapse. The results indicate that global response parameters, such as base-shear strength and mean drift ratio, are insufficient to explain the observed damage. The building had been designed with strength and stiffness characteristics comparable to other buildings that survived the earthquake with light to moderate damage. Investigation of the behavior of individual members leads to the conclusion that the building collapsed after the longitudinal reinforcement fractured in a first-story wall. This form of brittleness is related to under- rather than overreinforcement. The observed failure and data from laboratory tests demonstrate that minimum amounts of longitudinal reinforcement should be established in seismic-design requirements for structural walls.

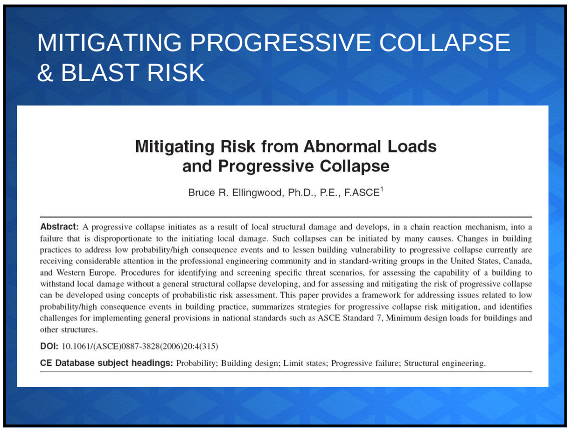
FIG. 3. Photograph of Damage to Wall M



ANOTHER LOOK AT THE L'AMBIANCE PLAZA COLLAPSE

By Rachel Martin[1] and Norbert J. Delatte,[2] Member, ASCE

ABSTRACT: The collapse of the L'Ambiance Plaza building, under construction in Bridgeport, Conn., in 1987, killed 28 construction workers. A number of concurrent investigations were undertaken to attempt to determine the cause. At least six separate theories were developed. However, a prompt legal settlement kept these investigations from being completed. This paper reviews the collapse and discusses the competing theories. The failure focused controversy on the safety of the lift-slab construction method. Because there is a need in civil engineering education for case studies to illustrate ethical and professional issues as well as technical principles, this paper also addresses these aspects. Ways for civil engineering educators to use this case study to address these issues also are discussed.



Mitigating Risk from Abnormal Loads and Progressive Collapse

Bruce R. Ellingwood, Ph.D., P.E., F.ASCE[1]

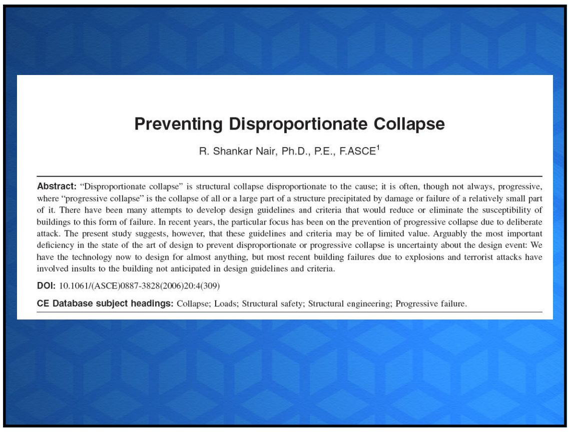
Abstract: A progressive collapse initiates as a result of local structural damage and develops, in a chain reaction mechanism, into a failure that is disproportionate to the initiating local damage. Such collapses can be initiated by many causes. Changes in building practices to address low probability/high consequence events and to lessen building vulnerability to progressive collapse currently are receiving considerable attention in the professional engineering community and in standard-writing groups in the United States, Canada, and Western Europe. Procedures for identifying and screening specific threat scenarios, for assessing the capability of a building to withstand local damage without a general structural collapse developing, and for assessing and mitigating the risk of progressive collapse can be developed using concepts of probabilistic risk assessment. This paper provides a framework for addressing issues related to low probability/high consequence events in building practice, summarizes strategies for progressive collapse risk mitigation, and identifies challenges for implementing general provisions in national standards such as ASCE Standard 7, Minimum design loads for buildings and other structures.

DOI: 10.1061/(ASCE)0887-3828(2006)20:4(315)

CE Database subject headings: Probability; Building design; Limit states; Progressive failure; Structural engineering.

Efforts of ASCE Regarding Building Stabilization after Abnormal Events

Amar Chaker



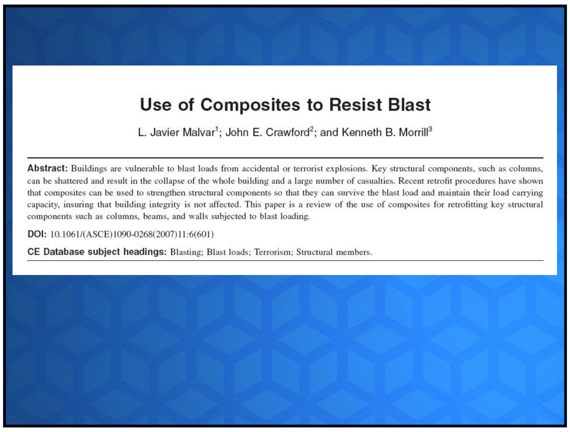
Preventing Disproportionate Collapse

R. Shankar Nair, Ph.D., P.E., F.ASCE[1]

Abstract: "Disproportionate collapse" is structural collapse disproportionate to the cause; it is often, though not always, progressive, where "progressive collapse" is the collapse of all or a large part of a structure precipitated by damage or failure of a relatively small part of it. There have been many attempts to develop design guidelines and criteria that would reduce or eliminate the susceptibility of buildings to this form of failure. In recent years, the particular focus has been on the prevention of progressive collapse due to deliberate attack. The present study suggests, however, that these guidelines and criteria may be of limited value. Arguably the most important deficiency in the state of the art of design to prevent disproportionate or progressive collapse is uncertainty about the design event: We have the technology now to design for almost anything, but most recent building failures due to explosions and terrorist attacks have involved insults to the building not anticipated in design guidelines and criteria.

DOI: 10.1061/(ASCE)0887-3828(2006)20:4(309)

CE Database subject headings: Collapse; Loads; Structural safety; Structural engineering; Progressive failure.



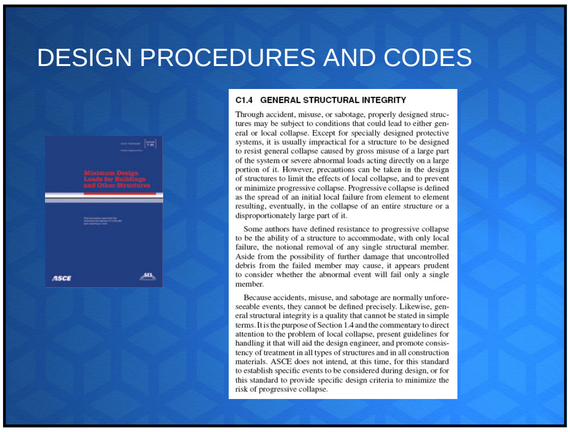
Use of Composites to Resist Blast

L. Javier Malvar[1]; John E. Crawford[2]; and Kenneth B. Morrill[3]

Abstract: Buildings are vulnerable to blast loads from accidental or terrorist explosions. Key structural components, such as columns, can be shattered and result in the collapse of the whole building and a large number of casualties. Recent retrofit procedures have shown that composites can be used to strengthen structural components so that they can survive the blast load and maintain their load carrying capacity, insuring that building integrity is not affected. This paper is a review of the use of composites for retrofitting key structural components such as columns, beams, and walls subjected to blast loading.

DOI: 10.1061/(ASCE)1090-0268(2007)11:6(601)

CE Database subject headings: Blasting; Blast loads; Terrorism; Structural members.

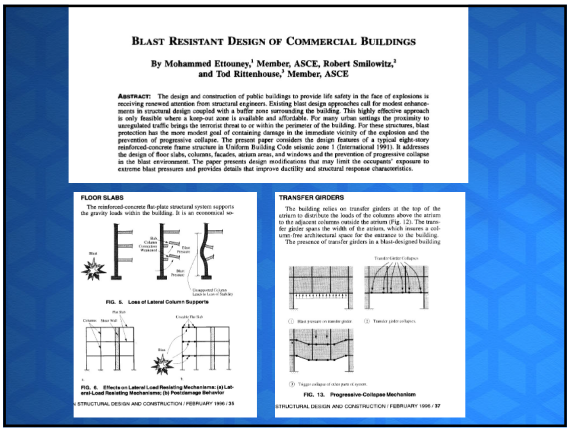


C1.4 GENERAL STRUCTURAL INTEGRITY

Through accident, misuse, or sabotage, properly designed structures may be subject to conditions that could lead to either general or local collapse. Except for specially designed protective systems, it is usually impractical for a structure to be designed to resist general collapse caused by gross misuse of a large part of the system or severe abnormal loads acting directly on a large portion of it. However, precautions can be taken in the design of structures to limit the effects of local collapse, and to prevent or minimize progressive collapse. Progressive collapse is defined as the spread of an initial local failure from element to element resulting, eventually, in the collapse of an entire structure or a disproportionately large part of it.

Some authors have defined resistance to progressive collapse to be the ability of a structure to accommodate, with only local failure, the notional removal of any single structural member. Aside from the possibility of further damage that uncontrolled debris from the failed member may cause, it appears prudent to consider whether the abnormal event will fail only a single member.

Because accidents, misuse, and sabotage are normally unforeseeable events, they cannot be defined precisely. Likewise, general structural integrity is a quality that cannot be stated in simple terms. It is the purpose of Section 1.4 and the commentary to direct attention to the problem of local collapse, present guidelines for handling it that will aid the design engineer, and promote consistency of treatment in all types of structures and in all construction materials. ASCE does not intend, at this time, for this standard to establish specific events to be considered during design, or for this standard to provide specific design criteria to minimize the risk of progressive collapse.



BLAST RESISTANT DESIGN OF COMMERCIAL BUILDINGS

By Mohammed Ettouney,[1] Member, ASCE, Robert Smilowitz,[2] and Tod Rittenhouse,[3] Member, ASCE

ABSTRACT: The design and construction of public buildings to provide life safety in the face of explosions is receiving renewed attention from structural engineers. Existing blast design approaches call for modest enhancements in structural design coupled with a buffer zone surrounding the building. This highly effective approach is only feasible where a keep-out zone is available and affordable. For many urban settings the proximity to unregulated traffic brings the terrorist threat to or within the perimeter of the building. For these structures, blast protection has the more modest goal of containing damage in the immediate vicinity of the explosion and the prevention of progressive collapse. The present paper considers the design features of a typical eight-story reinforced-concrete frame structure in Uniform Building Code seismic zone 1 (International 1991). It addresses the design of floor slabs, columns, facades, atrium areas, and windows and the prevention of progressive collapse in the blast environment. The paper presents design modifications that may limit the occupants' exposure to extreme blast pressures and provides details that improve ductility and structural response characteristics.

FLOOR SLABS

The reinforced-concrete flat-plate structural system supports the gravity loads within the building. It is an economical so-

FIG. 5. Loss of Lateral Column Supports

FIG. 6. Effects on Lateral Load Resisting Mechanisms: (a) Lateral-Load Resisting Mechanisms; (b) Postdamage Behavior

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TRANSFER GIRDERS

The building relies on transfer girders at the top of the atrium to distribute the loads of the columns above the atrium to the adjacent columns outside the atrium (Fig. 12). The transfer girder spans the width of the atrium, which insures a column-free architectural space for the entrance to the building.

The presence of transfer girders in a blast-designed building

FIG. 13. Progressive-Collapse Mechanism

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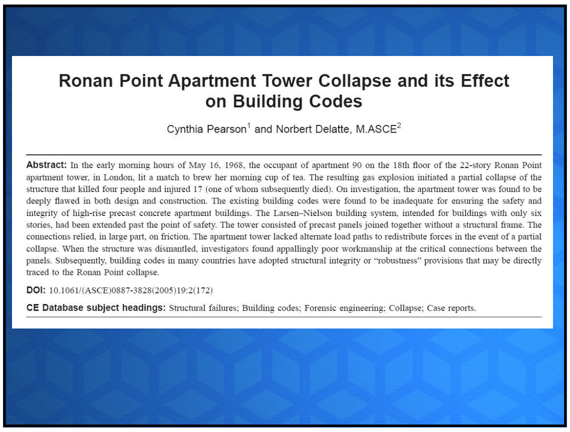


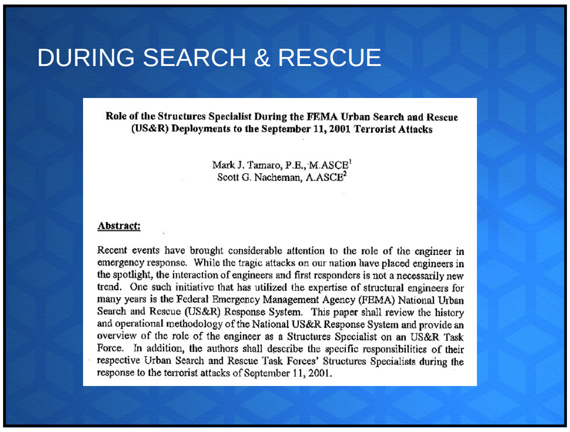
Ronan Point Apartment Tower Collapse and its Effect on Building Codes

Cynthia Pearson[1] and Norbert Delatte, M.ASCE[2]

Abstract: In the early morning hours of May 16, 1968, the occupant of apartment 90 on the 18th floor of the 22-story Ronan Point apartment tower, in London, lit a match to brew her morning cup of tea. The resulting gas explosion initiated a partial collapse of the structure that killed four people and injured 17 (one of whom subsequently died). On investigation, the apartment tower was found to be deeply flawed in both design and construction. The existing building codes were found to be inadequate for ensuring the safety and integrity of high-rise precast concrete apartment buildings. The Larsen–Nielson building system, intended for buildings with only six stories, had been extended past the point of safety. The tower consisted of precast panels joined together without a structural frame. The connections relied, in large part, on friction. The apartment tower lacked alternate load paths to redistribute forces in the event of a partial collapse. When the structure was dismantled, investigators found appallingly poor workmanship at the critical connections between the panels. Subsequently, building codes in many countries have adopted structural integrity or "robustness" provisions that may be directly traced to the Ronan Point collapse.

DOI: 10.1061/(ASCE)0887-3828(2005)19:2(172)

CE Database subject headings: Structural failures; Building codes; Forensic engineering; Collapse; Case reports.



Role of the Structures Specialist During the FEMA Urban Search and Rescue (US&R) Deployments to the September 11, 2001 Terrorist Attacks

Mark J. Tamaro, P.E., M.ASCE[1]
Scott G. Nacheman, A.ASCE[2]

Abstract:

Recent events have brought considerable attention to the role of the engineer in emergency response. While the tragic attacks on our nation have placed engineers in the spotlight, the interaction of engineers and first responders is not a necessarily new trend. One such initiative that has utilized the expertise of structural engineers for many years is the Federal Emergency Management Agency (FEMA) National Urban Search and Rescue (US&R) Response System. This paper shall review the history and operational methodology of the National US&R Response System and provide an overview of the role of the engineer as a Structures Specialist on an US&R Task Force. In addition, the authors shall describe the specific responsibilities of their respective Urban Search and Rescue Task Forces' Structures Specialists during the response to the terrorist attacks of September 11, 2001.

Efforts of ASCE Regarding Building Stabilization after Abnormal Events
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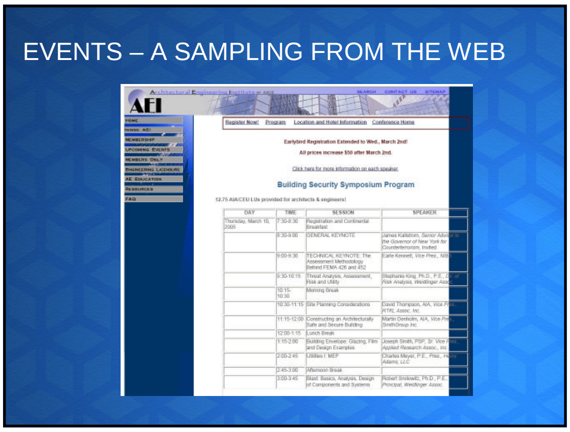
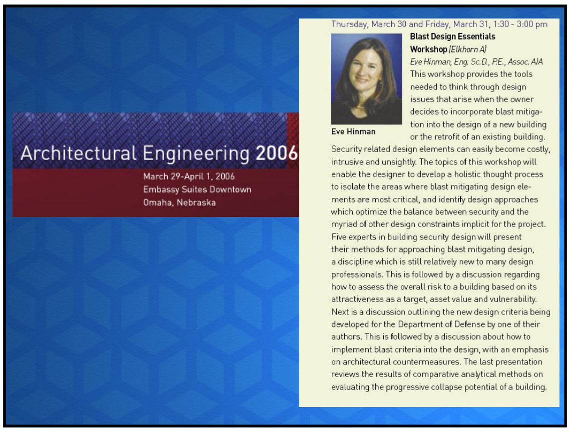
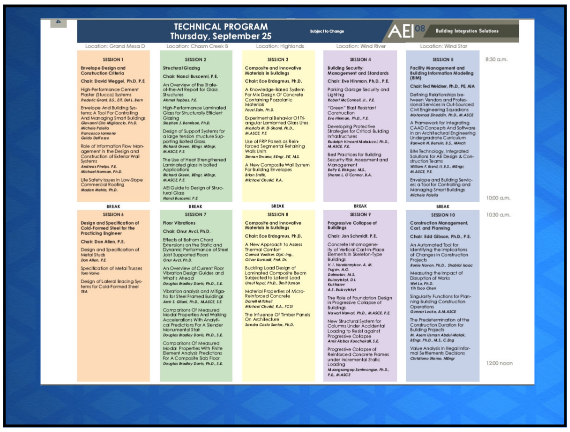
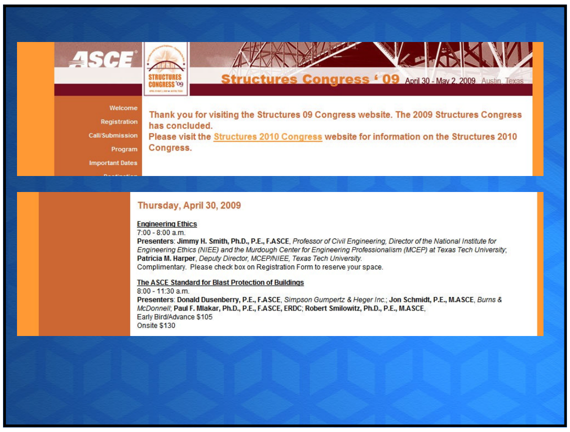
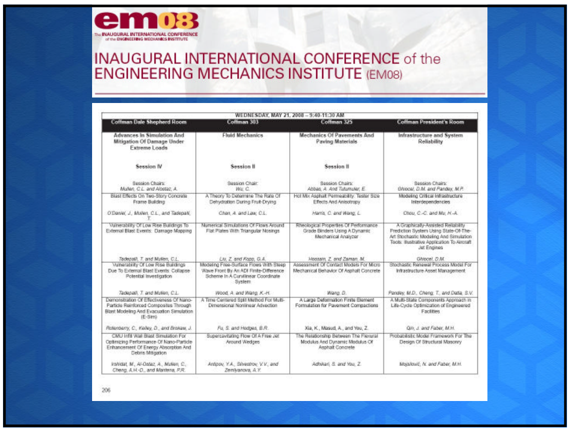










Efforts of ASCE Regarding Building Stabilization after Abnormal Events

Amar Chaker

Continuing Education ASCE

PROGRESSIVE COLLAPSE MITIGATION: PRACTICAL ANALYSIS METHODS AND PROVEN SOLUTIONS

Boston, MA / May 28-29, 2009

San Francisco, CA / September 10-11, 2009

ON-GOING COMMITTEE ACTIVITIES – A SAMPLING OF REPLIES

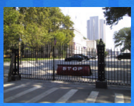
- **The SEI Reliability-Based Structural System Performance Indicators Committee (just established):**
  - **Will work on assembling a document on the current state of the art related to the development and implementation of reliability-based structural performance indicators and criteria at both the component and system levels taking into consideration the uncertainties in evaluating the performance of structures subjected to uncertain loading conditions. Some of the issues that we plan to address include: a) time-dependent component safety (structural members and connections), b) serviceability, c) system safety, d) redundancy, and e) robustness. Methods used for establishing appropriate limit sates for assessing the different performance levels will be investigated. Approaches for analyzing the progressive collapse of complex systems with multiple failure modes will be reviewed along with how structural uncertainties are accounted for in this context. The paper will also review the feasibility of implementing criteria for the analysis of system and network resiliency and recovery time. Methods for studying the effect of scaling and the relative importance of components and systems at different scale levels of a network will be studied.**

- **AED Committee on Mitigation of Effects of Terrorism (formed May 1995)**
  - Scoping Conference on Mitigation of Terrorist Violence held at John Jay College, City University of New York on 23 June 1995, determines major fatalities in Oklahoma City caused by progressive building collapse while major casualties caused by flying debris, mainly shattered glass. Speakers: N. J. Glover, Aegis, T. Rittenhouse, Weidlinger Associates, Inc., R. J. Loudon, Dir. CUNY Crim. Just. Ctr., James Standish, Flack & Kurtz

BUILDING SECURITY COUNCIL RATING SYSTEM

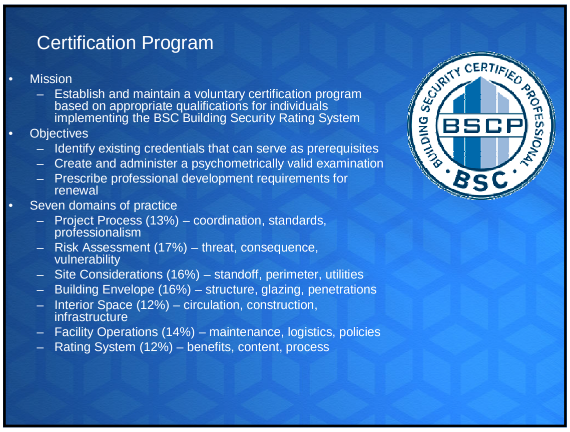
- PLUS[SM] - Promoting Logical Unified Security
  - A rating system that organizes countermeasures into logical and comprehensive combinations that can be quantified
  - A reasonable response based on building classification and Owner needs
  - A system to promote innovation and unified multi-disciplinary solutions
  - A system vetted by the Department of Homeland Security and that received SAFETY Act designation

- Countermeasure Checklists
  - Organized and weighted by FEMA 426 discipline
    - Site
    - Architectural
    - Structural
    - Building Envelope
    - Utilities
    - Mechanical
    - Plumbing & Gas
    - Electrical
    - Fire
    - Communications & IT
    - Equipment Operations & Maintenance
    - Security Systems
    - Security Master Plan



- References
  - FEMA Risk Management Series
    - FEMA 426, *Reference Manual to Mitigate Potential Terrorist Attacks Against Buildings*
  - Interagency Security Committee
    - *Security Design Criteria for New Federal Office Buildings and Major Modernization Projects*
  - Department of Defense Unified Facilities Criteria
    - UFC 4-010-01, *DoD Minimum Antiterrorism Standards for Buildings*

Efforts of ASCE Regarding Building Stabilization after Abnormal Events
Amar Chaker



The Pentagon Building Performance

Paul F. Mlakar, Ph.D., P.E.
U.S. Army Engineer Research and Development Center

US Army Corps of Engineers

ASCE Building Performance Studies

Hurricane Andrew

Oklahoma City Bombing

US Army Corps of Engineers

Outline

- **The Pentagon**
- **9/11 Crash**
- **Structural Response**

US Army Corps of Engineers

Pentagon Team

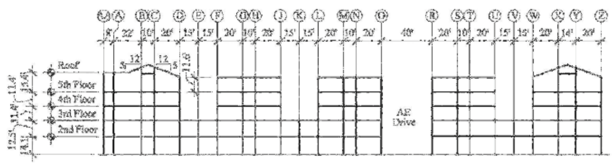
- **Paul F. Mlakar, Ph.D., P.E., Lead**
  U.S. Army Corps of Engineers
- **Donald Dusenberry, P.E.**
  Simpson Gumpertz & Heger, Inc.
- **James Harris, Ph.D., P.E.**
  J. R. Harris & Company
- **Gerald Haynes, P.E.**
  Bureau of Alcohol, Tobacco and Firearms
- **Long Phan, Ph.D., P.E.**
  National Institute of Standards and Technology
- **Mete Sozen, Ph.D., P.E.**
  Purdue University

US Army Corps of Engineers

The Pentagon

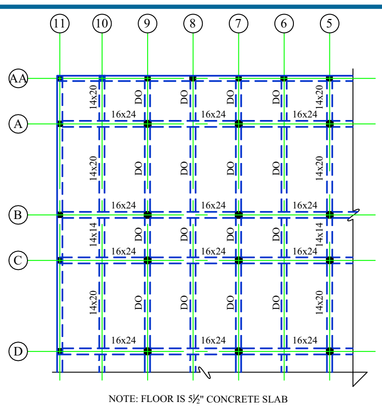
US Army Corps of Engineers

Cross Section



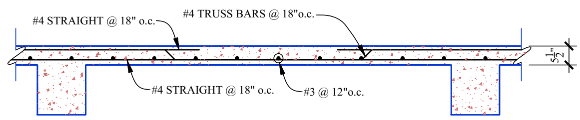
US Army Corps of Engineers

Structural Framing



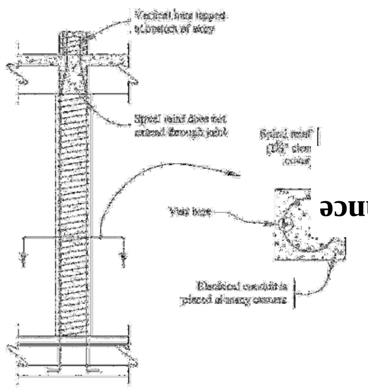
US Army Corps of Engineers

Reinforcement of Floor Slabs



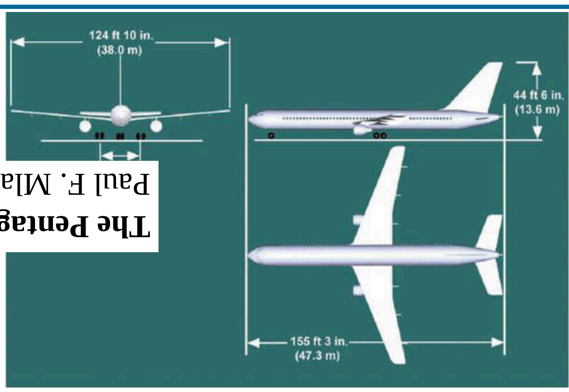
US Army Corps of Engineers

Spirally Reinforced Columns



US Army Corps of Engineers

B757-200 Aircraft



The Pentagon Building Performance
Paul F. Mlakar

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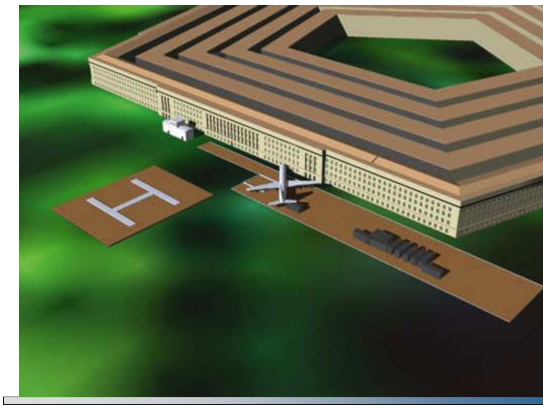
Aircraft Impact

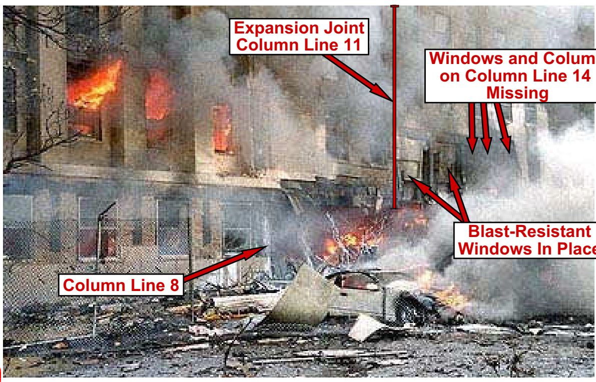
US Army Corps of Engineers

Aircraft at Impact



US Army Corps of Engineers

Northern Portion of Impact Area



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Southern Portion of Impact Area

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Partial Collapse

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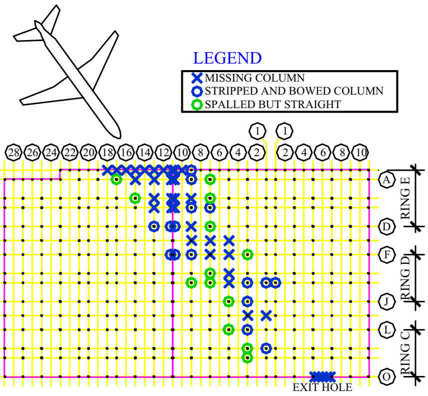
Impact Damage to Columns



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Impact Damage

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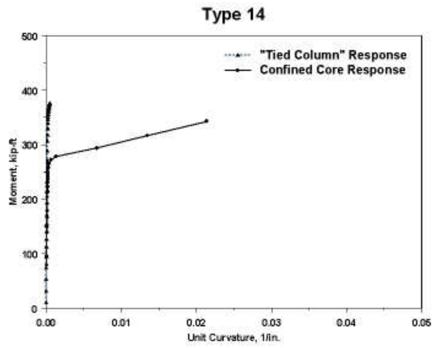
Exit Hole

US Army Corps of Engineers

Stripped Column

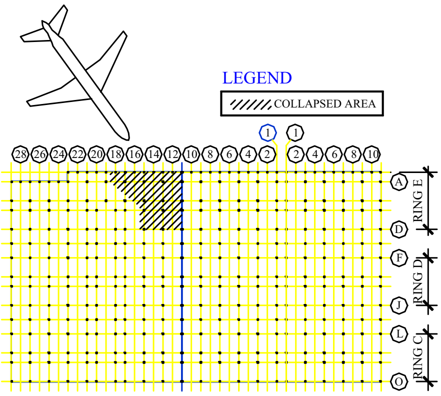
US Army Corps of Engineers

Lateral Resistance of Columns



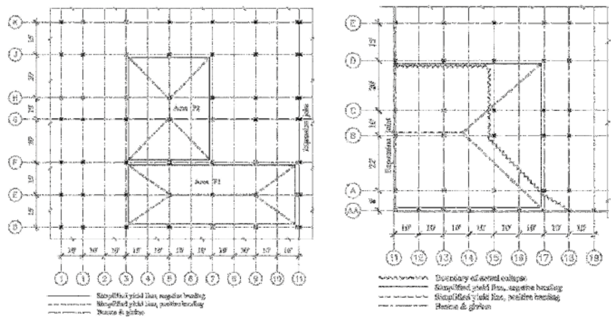
US Army Corps of Engineers

Limit of Collapse



US Army Corps of Engineers

Analysis of Floor System



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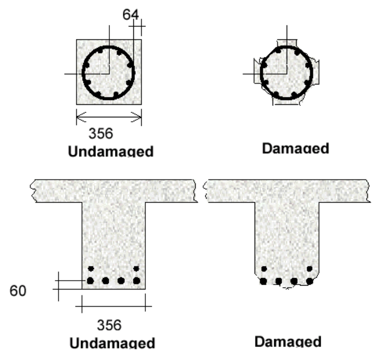
Thermal Cracking of Column

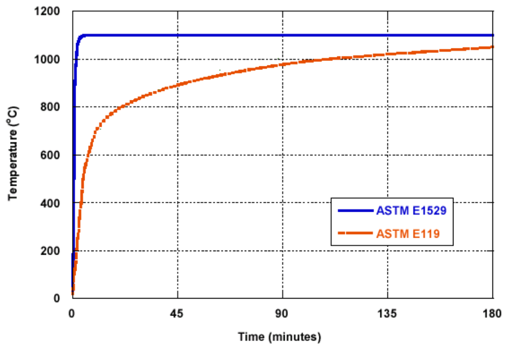
US Army Corps of Engineers

Thermal Analysis



US Army Corps of Engineers

Thermal Loading



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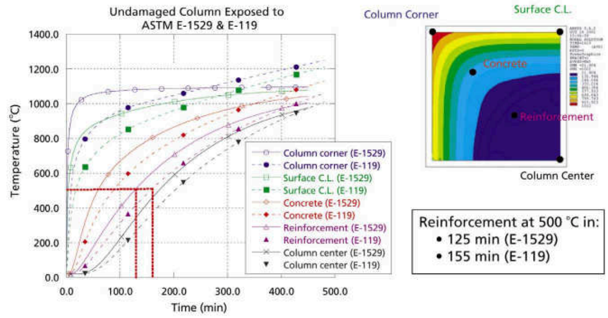
Thermal Response



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Time to Yield of Reinforcing Bars

Member	Condition	Fire	Time to Yield min
Column	Undamaged	Office	155
Column	Undamaged	Fuel	125
Column	Stripped	Office	50
Column	Stripped	Fuel	25
Girder	Undamaged	Office	130
Girder	Undamaged	Fuel	100
Girder	Stripped	Office	20
Girder	Stripped	Fuel	12

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Recommendations

- **ASCE 7: "…sustain local damage with the structural system as a whole remaining stable…"**
  - **Continuity**
  - **Redundancy**
  - **Energy-absorption**

US Army Corps of Engineers

Questions?

US Army Corps of Engineers

NIST Efforts to Prevent Disproportionate Collapse of Buildings
H.S. Lew and S.A. Cauffman

NIST EFFORTS TO PREVENT DISPROPORTIONATE COLLAPSE OF BUILDINGS

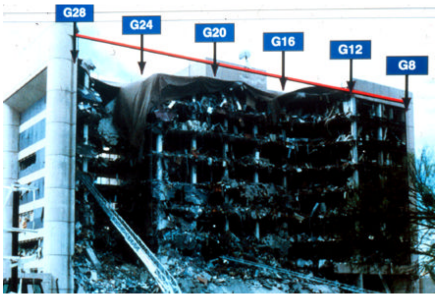
Stabilization of Buildings Workshop
ERDC, Vicksburg
August 25, 2009

H. S. Lew
S.A. Cauffman
Building and Fire Research Laboratory
National Institute of Standards and Technology
hsl@nist.gov

NIST National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Alfred P. Murrah Federal Building

(April 19, 1995)



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Collapse of World Trade Center Towers

(September 11, 2001)

NIST National Institute of Standards and Technology
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First Interstate Bank

(May 4, 1988)

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Technology Administration, U.S. Department of Commerce

PROBLEM STATEMENT

- Many U.S. buildings are vulnerable to extreme loads that may cause partial or total collapse.
- Modern structures have a limited reserve capacity to accommodate abnormal loads.
- Accepted metrics for defining and quantifying the reserve capacity is lacking within multi-hazard context.
- System behavior is not well understood and depends on connection performance, which is highly nonlinear and complex.
- Analytical tools addressing structural failures are complex and experimentally-validated analytical tools are not available, and modeling of structural system response up to failure (post peak capacity) is challenging.

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NIST'S RESEARCH PROGRAM

- Limit state characterization based on structural system failure.
- Metrics for structural robustness/redundancy.
- Experimentally validated component/connection/subassemblage failure modes.
- Development of validated analytical tools for assessment of disproportionate collapse potential and design.
- Identification of structural systems capable of arresting failure propagation.

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NIST Efforts to Prevent Disproportionate Collapse of Buildings
H.S. Lew and S.A. Cauffman

NIST PROGRAM OBJECTIVE

To enhance robustness of building structures through the development and implementation of:

- Metrics for structural robustness
- Performance criteria for codes and standards
- Analytical tools for design professionals
- Practical guidelines

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PROGRAM ROADMAP

- ❑ Best Practices Guide for design of new buildings and rehabilitation of existing buildings.
- ❑ Comparative assessment of reserve capacities of various structural systems; thereby identifying relative robustness of structural systems.
- ❑ Guidelines for assessing disproportionate collapse vulnerability. This includes both rapid and comprehensive evaluation guides.
- ❑ Comprehensive guidelines for design of new buildings to resist disproportionate collapse.
- ❑ Comprehensive guidelines for retrofit of existing buildings to resist disproportionate collapse.
- ❑ Pre-standards for design of new buildings to resist disproportionate collapse.

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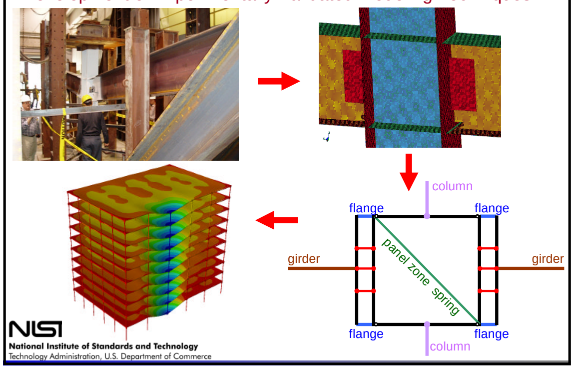
Technical Approach:

Development of Experimentally Validated Modeling Techniques



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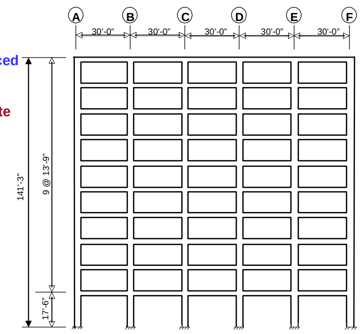
Buildings Design

Design of steel and reinforced concrete buildings for:

SDC C – Atlanta (moderate seismic region)
SDC D – Seattle (high seismic region)

Building Types:

- Steel moment frame
- Steel braced frame
- Concrete moment frame
- Concrete shear wall
- Precast concrete frame



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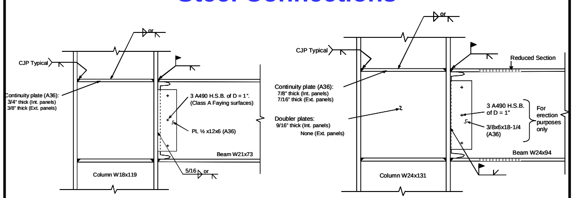
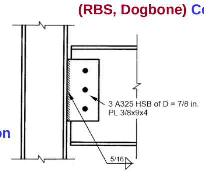
Steel Connections



Welded Unreinforced Flange – Bolted Web (WUF-B) Connection

Reduced Beam Section (RBS, Dogbone) Connection



Single Plate Shear (Shear Tab) Connection

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NIST Efforts to Prevent Disproportionate Collapse of Buildings

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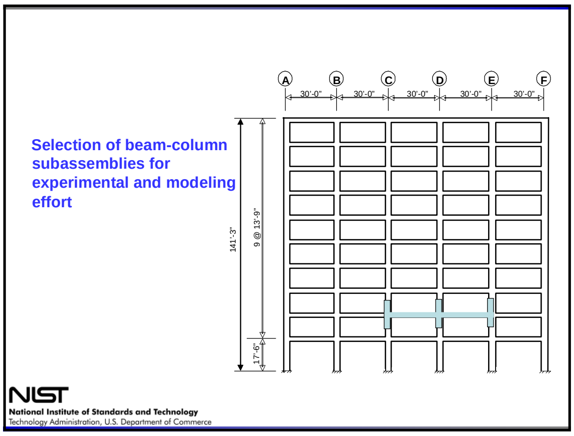

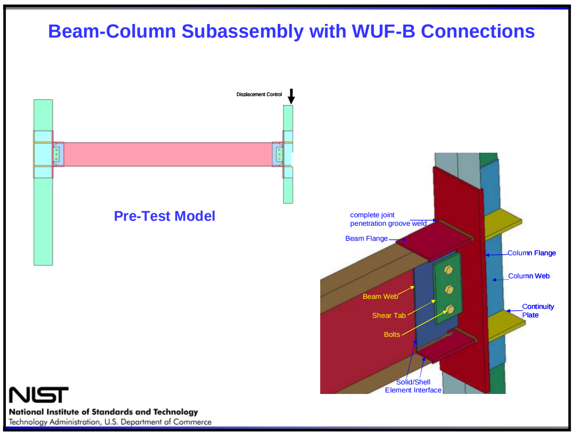

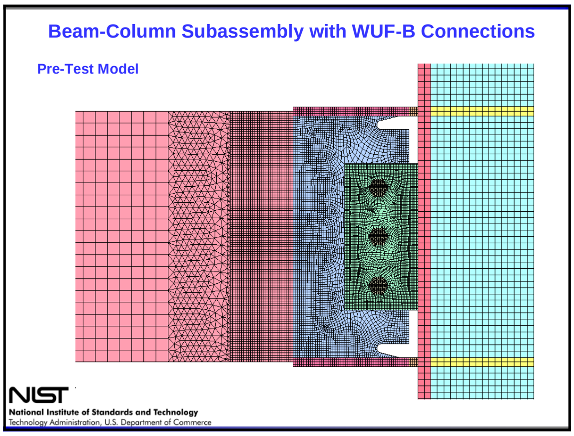

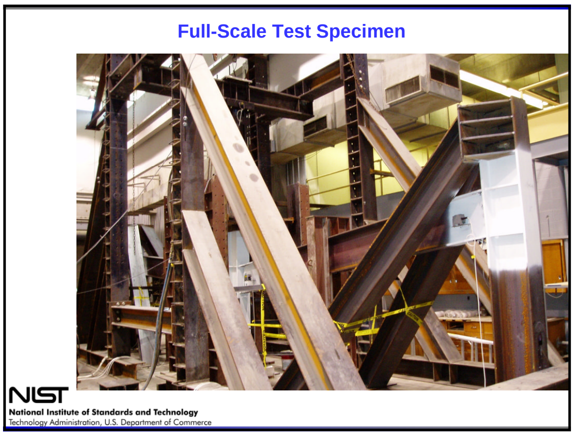

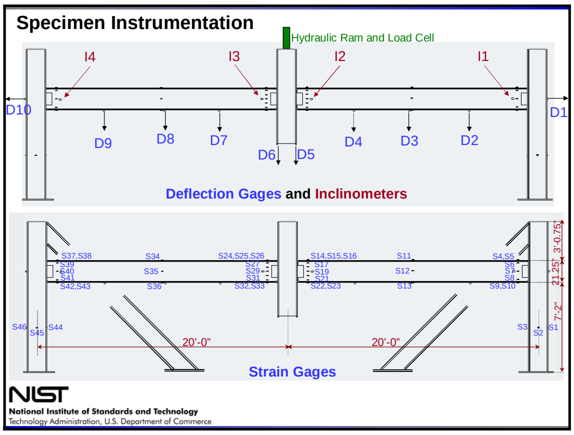

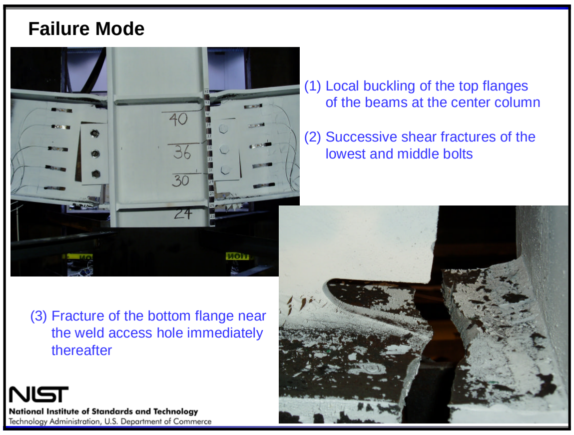

WUF-B: Pre-test Prediction vs. Experiment

	Pre-Test Prediction	Experiment
Ultimate Load	190 kips	200 kips
Corresponding Displacement	20 in	19.5 in
Failure Mode	• Failure of shear tab • Fracture of tension flange (at top flange near ext. column)	• Shearing-off of bolts • Fracture of tension flange (at bottom flange near center column)

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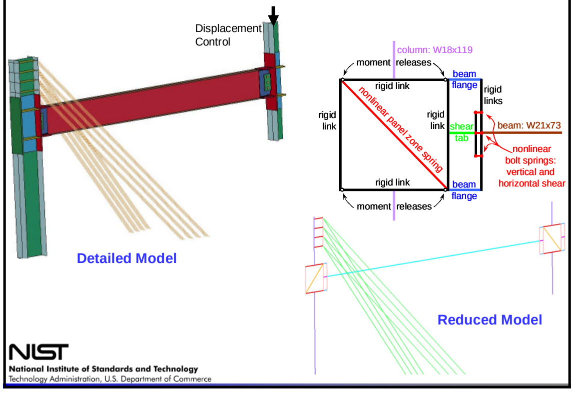
Post-Test Models



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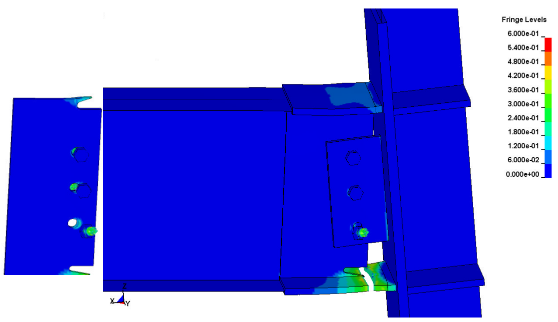

Bolt Failure and Flange Fracture (displacement of 20 in.)

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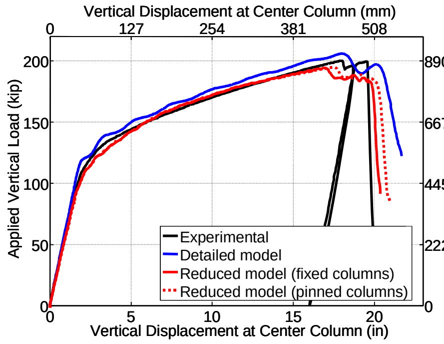
Center Column Load vs. Vertical Deflection WUF - Bolted



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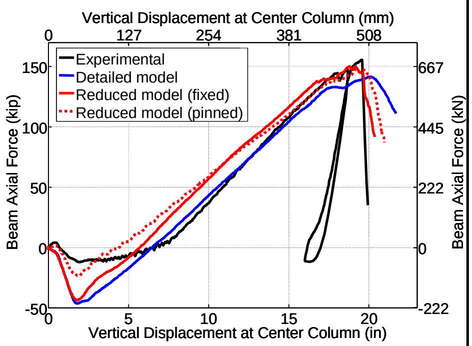
Axial Force in Beam vs. Deflection



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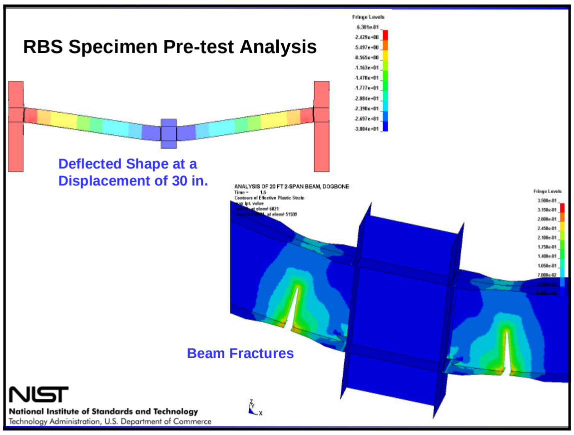
RBS Specimen Pre-test Analysis



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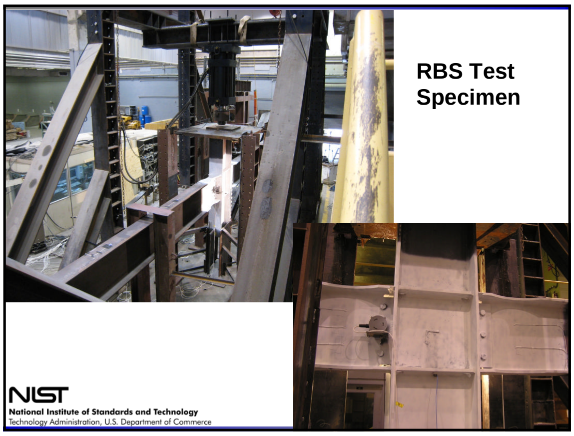

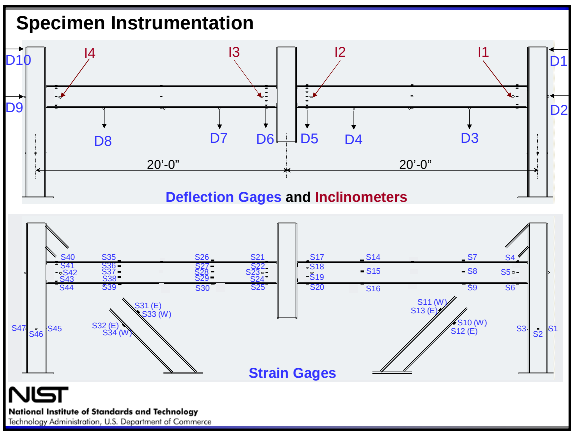

RBS: Pre-test Prediction vs. Experiment

	Pre-Test Prediction	Experiment
Ultimate Load	365 kips	396 kips
Corresponding Displacement	31 in	34 in
Failure Mode ✔	• Fracture of the bottom flange propagated into web in the middle of the reduced section	• Fracture of the bottom flange propagated into web in the middle of the reduced section

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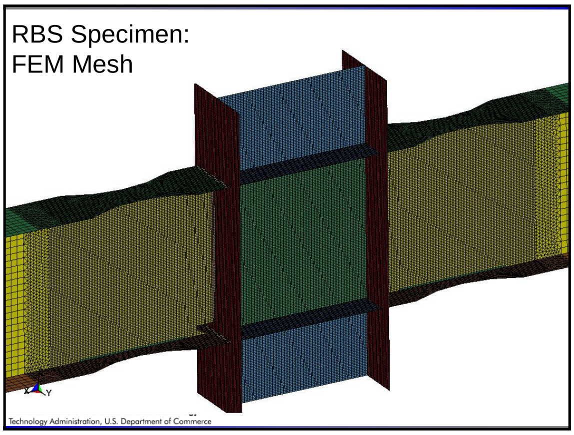
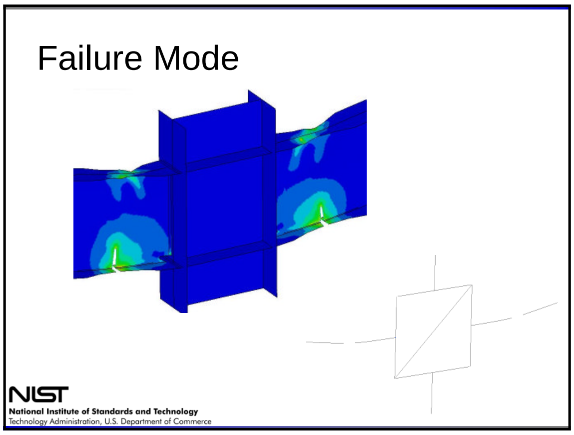
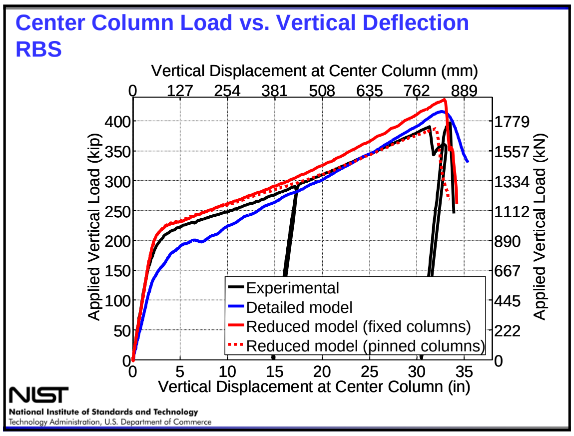
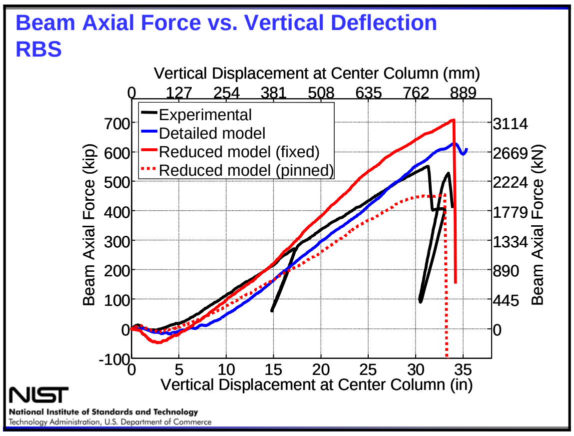
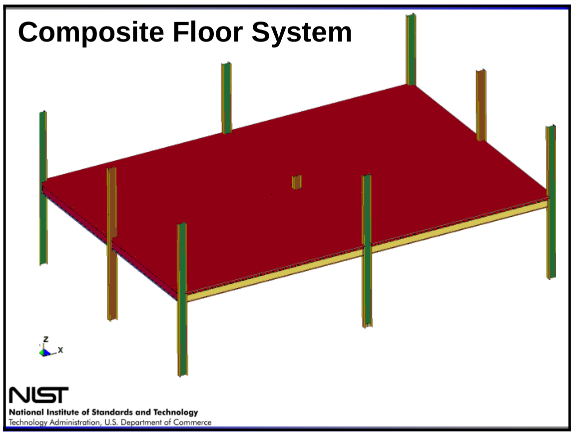


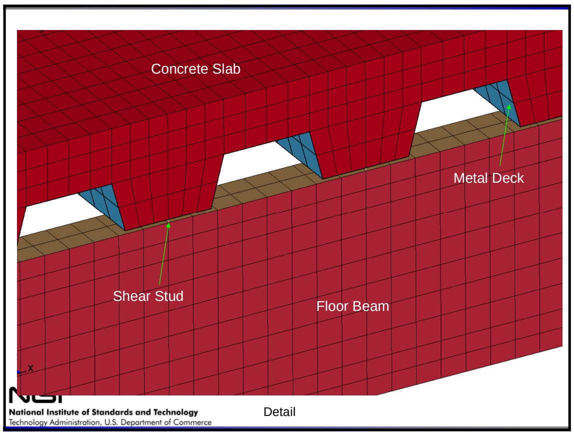


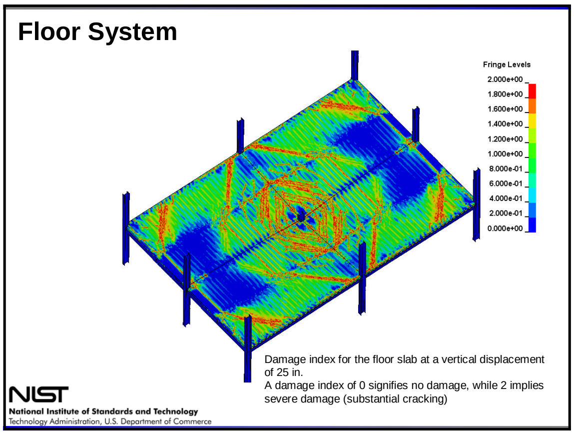
NIST Efforts to Prevent Disproportionate Collapse of Buildings
H.S. Lew and S.A. Cauffman

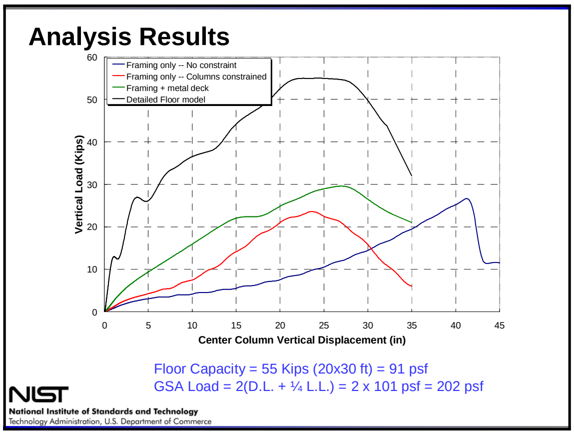


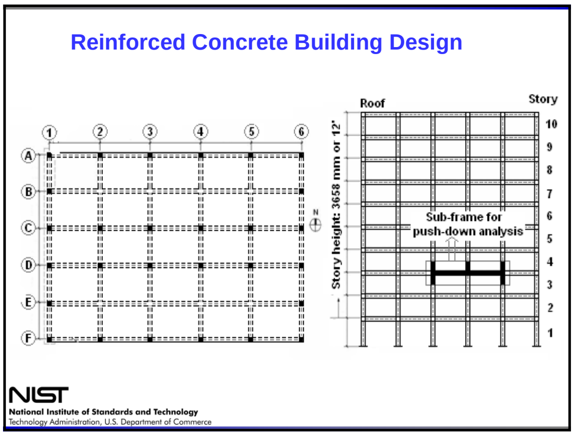











Reinforced Concrete Building Design
Roof
Story
Story height: 3658 mm or 12'
Sub-frame for
push-down analysis
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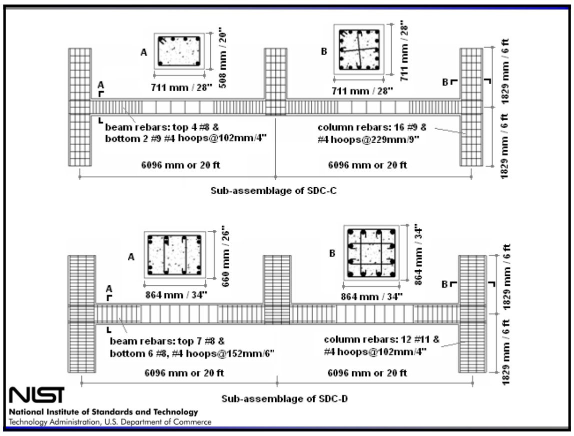
711 mm / 28"
508 mm / 20"
beam rebars: top 4 #8 &
bottom 2 #9 #4 hoops@102mm/4"
column rebars: 16 #9 &
#4 hoops@229mm/9"
6096 mm or 20 ft
1829 mm / 6 ft
Sub-assemblage of SDC-C
864 mm / 34"
660 mm / 26"
beam rebars: top 7 #8 &
bottom 6 #8, #4 hoops@152mm/6"
column rebars: 12 #11 &
#4 hoops@102mm/4"
Sub-assemblage of SDC-D
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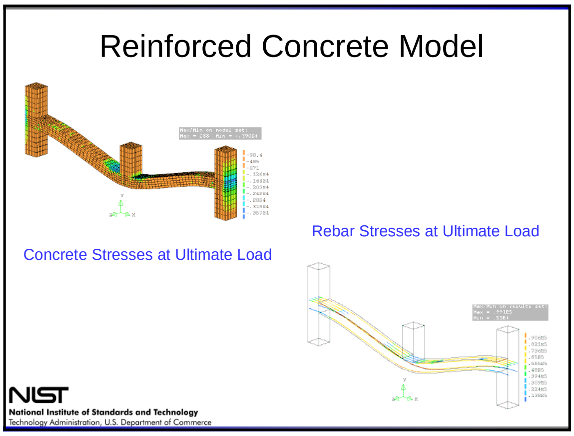
Reinforced Concrete Model
Concrete Stresses at Ultimate Load
Rebar Stresses at Ultimate Load
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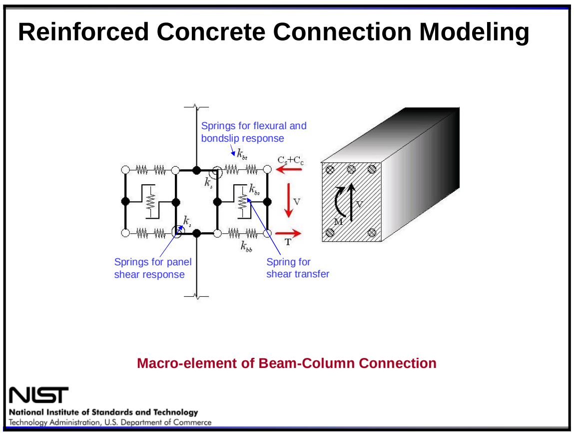
Reinforced Concrete Connection Modeling
Springs for flexural and
bondslip response
Springs for panel
shear response
Spring for
shear transfer
Macro-element of Beam-Column Connection
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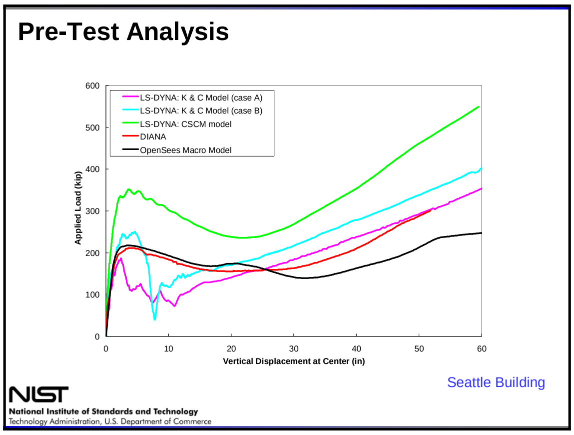
Pre-Test Analysis
LS-DYNA: K & C Model (case A)
LS-DYNA: K & C Model (case B)
LS-DYNA: CSCM model
DIANA
OpenSees Macro Model
Applied Load (kip)
Vertical Displacement at Center (in)
Seattle Building
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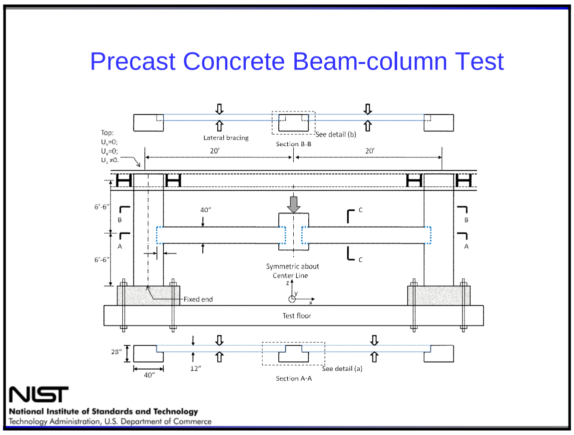
Precast Concrete Beam-column Test
Lateral bracing
Section B-B
See detail (b)
Symmetric about
Center Line
Fixed end
Test floor
Section A-A
See detail (a)
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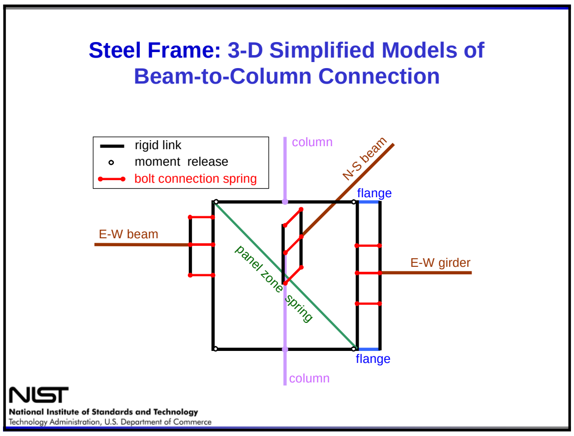
Steel Frame: 3-D Simplified Models of Beam-to-Column Connection
rigid link
moment release
bolt connection spring
column
N-S beam
flange
E-W beam
panel zone spring
E-W girder
flange
column
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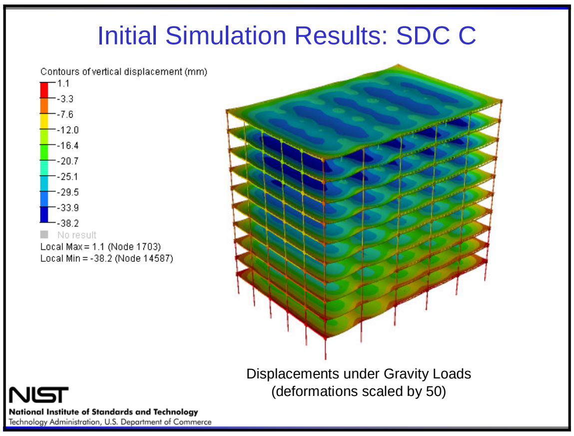
Initial Simulation Results: SDC C
Contours of vertical displacement (mm)
1.1
-3.3
-7.6
-12.0
-16.4
-20.7
-25.1
-29.5
-33.9
-38.2
No result
Local Max = 1.1 (Node 1703)
Local Min = -38.2 (Node 14587)
Displacements under Gravity Loads
(deformations scaled by 50)
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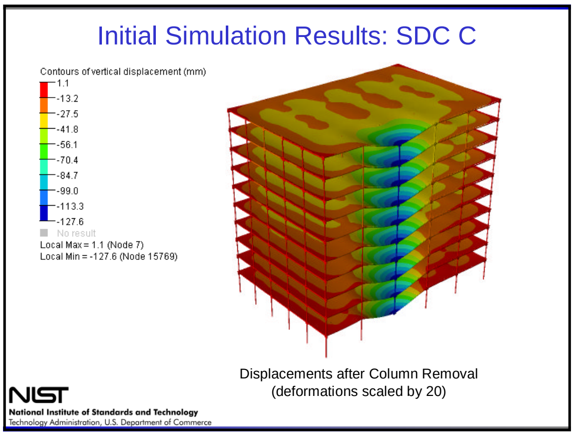
Initial Simulation Results: SDC C
Contours of vertical displacement (mm)
1.1
-13.2
-27.5
-41.8
-56.1
-70.4
-84.7
-99.0
-113.3
-127.6
No result
Local Max = 1.1 (Node 7)
Local Min = -127.6 (Node 15769)
Displacements after Column Removal
(deformations scaled by 20)
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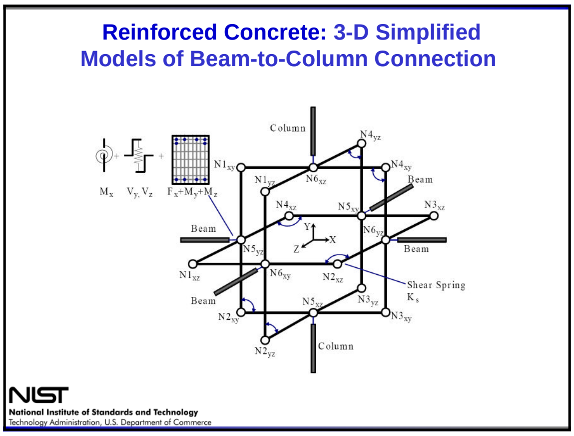
Reinforced Concrete: 3-D Simplified Models of Beam-to-Column Connection
Column
Beam
Beam
Beam
Shear Spring
Column
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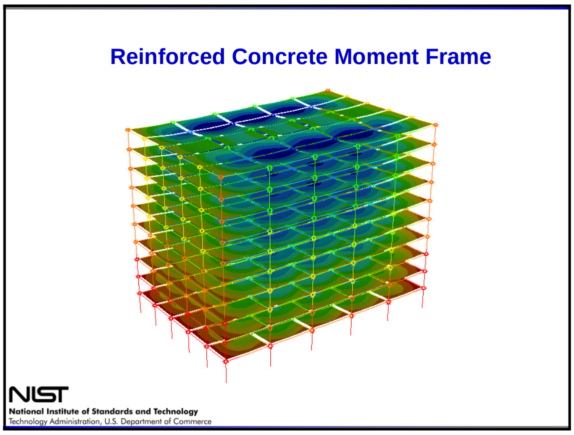
Reinforced Concrete Moment Frame
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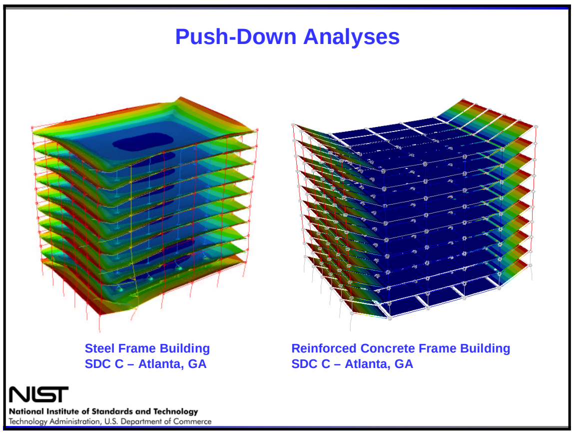
Push-Down Analyses
Steel Frame Building
SDC C – Atlanta, GA
Reinforced Concrete Frame Building
SDC C – Atlanta, GA
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NIST Efforts to Prevent Disproportionate Collapse of Buildings
H.S. Lew and S.A. Cauffman

PROGRAM ROADMAP

- Best Practices Guide for design of new buildings and rehabilitation of existing buildings.
- Comparative assessment of reserve capacities of various structural systems; thereby identifying relative robustness of structural systems.
- Guidelines for assessing disproportionate collapse vulnerability. This includes both rapid and comprehensive evaluation guides.
- Comprehensive guidelines for design of new buildings to resist disproportionate collapse.
- Comprehensive guidelines for retrofit of existing buildings to resist disproportionate collapse.
- Pre-standards for design of new buildings to resist disproportionate collapse.

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Questions ?

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Real Time General Assessment Issues
Philip E. Parr

Philip E. Parr

Federal Coordinating Officer

FEMA

Battalion Chief FDNY
Retired

Death and Injury Statistics

- Each year > 100 firefighters die LOD deaths
- Each year another 100,000 injured
  - 1 FF death every 3 days
  - 8,000 firefighter injuries every month

If a firefighter dies while combating a blaze, that death will be caused by the extreme physical and emotional stress of firefighting while pulling a hose line or raising a ladder, an apparatus accident while responding or returning from alarms, falling off a smoky roof at night, being trapped by smoke and flame, or…

OR BEING BURIED ALIVE UNDER TONES OF BRICKS AND TIMBERS DURING A STRUCTURAL COLLAPSE.

Safety and survival on the fireground; Vincent Dunn; 1992

Collapse

Depending on the year collapse is the 4th or 5th leading cause of LOD FF deaths

- Collapse leads to multiple FF deaths or inj
  - Chicago 21 FF died in collapse of a stockyard building in 1910
  - Same year Philadelphia lost 14 FF as a result of a collapse in a leather factor building
  - Oct 17, 1966 NYC lost 12 FFs when floor collapsed plunging them into a burning cellar

Definition of Collapse

- Any portion of a structure that fails as a result of fire — Dunn
- Falling object
- Falls
- Exposure to fire products

General Building Construction Types

- Fire Resistive
- Non-Combustible / limited combustible
- Ordinary Brick and Joist
- Heavy Timber
- Wood frame

Collapse Dangers

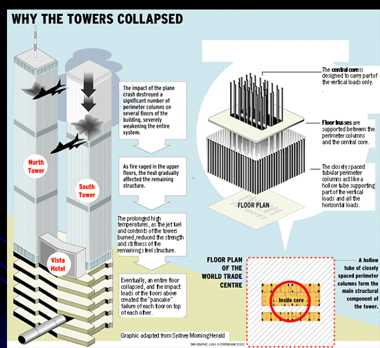
- Fire Resistive
  - Concrete Spalling/heaving
- Non-Combustible / limited combustible
  - Roof collapse/light weight steel bar joist
- Ordinary Brick and Joist
  - Parapet wall collapse
- Heavy Timber
  - Floor collapse -> Wall collapse
- Wood frame
  - 2x4 walls supporting larger structural materials

Chief Officer Evaluations

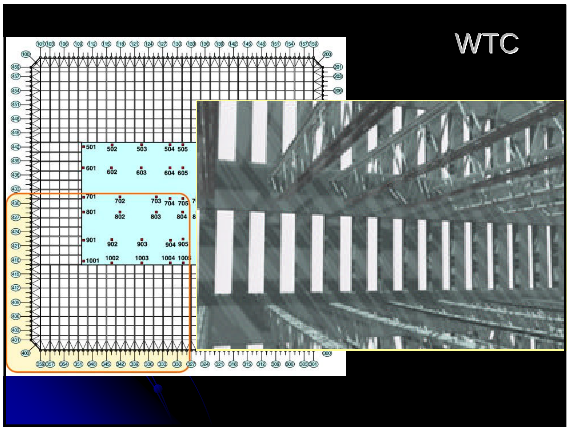
- Time
- New Light Weight Construction Materials

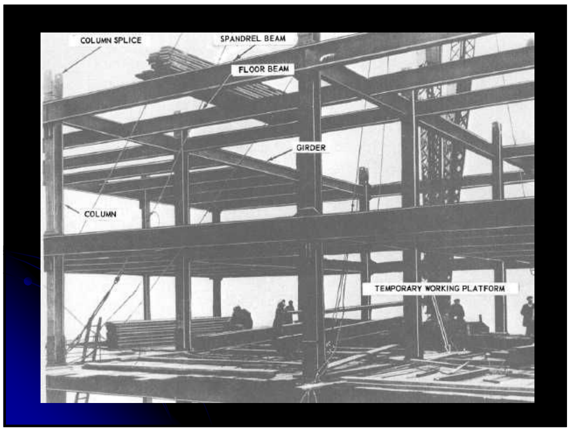
Surprising Cause of Collapse

WTC



Real Time General Assessment Issues
Philip E. Parr





Monitoring Stability Loss in Burning Buildings

Can it really be done?

Presented by

Zee Duron

Harvey Mudd College

Stabilization of Buildings Workshop 2009

In Theory, we think that

- Fire produces a random broad-band excitation
- An irreversible process beings at ignition that weakens the structure
- Measured responses can be interpreted and correlated in the context of transient events during burn
- Fire induces structural vibrations
- Fire-induced vibrations can be measured during burn
- Fire-induced vibrations can be used to monitor impending collapse
- *A practical field approach will result if some indication of impending stability loss can be achieved*

Field Experience leads to

- Practical considerations for monitoring structural response
  - Must be independent of structure type, construction materials, or excitation
  - Must provide capability for monitoring response beyond "traditional frequency range of interest"
  - Sensor parameters must be selected for low SNR, high sample rates, and high sensitivities
  - Simplified stability indicator algorithms could work

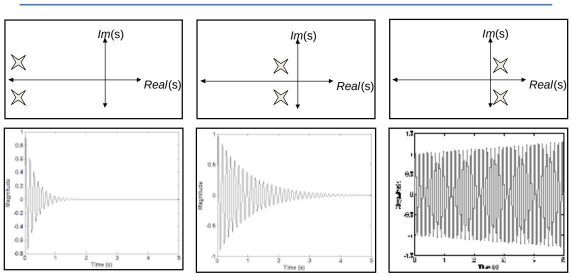
"Black Box Model"

Fire → Building → *Structural Vibrations*

Traditional Systems Theory predicts behavior based on "inputs and outputs" and the ratio of these.

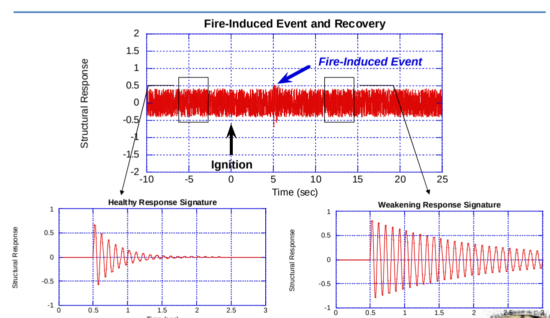
Not knowing what the system is does not prohibit system characterization.

Principles of Stability Theory



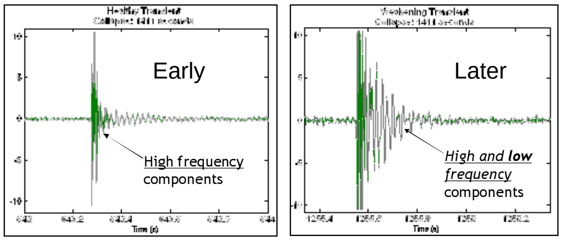
Poles and Stable Behavior
Poles contain information on frequency and damping

Observational Evidence



Sample Field Data

- As burning continues, the transients take longer to return to original levels



Civil Engineers think

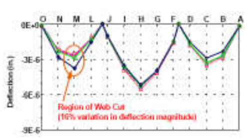
- Traditional approaches to structural or earthquake monitoring are limited to frequency ranges defined by dominant structural or ground frequency content.
- Caltech/USGS and the Southern California Seismic Network sample responses at 200 sps
  - The Reagan Medical Center is sampled at 500 sps
- *It is well known that changes in structural frequencies do not track well with damage or impending collapse*

e.g. Sycamore Bridge

$$[H(\omega=0)] = \frac{1}{[K]} = [f] = flexibility$$

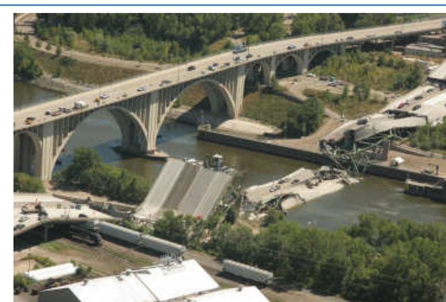
$$[f] = \sum_{r=1}^{N}\left[\frac{\{\psi\}_r\{\psi\}_r^T}{M_{A_r}(-\lambda_r)} + \frac{\{\psi^*\}_r\{\psi^*\}_r^T}{M_{A_r}^*(-\lambda_r^*)}\right]$$

Essentially, the flexibility matrix, [f], may be interpreted as the frequency response function matrix, [H(ω)], at zero frequency [Catbas et. al. 1997].



$\Delta f_{fundamental} \approx 6\%$ $\Delta wavespeed \approx 38\%$

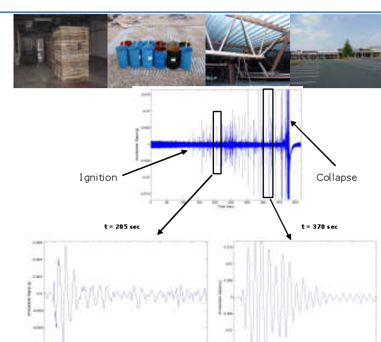
I35W Bridge Collapse



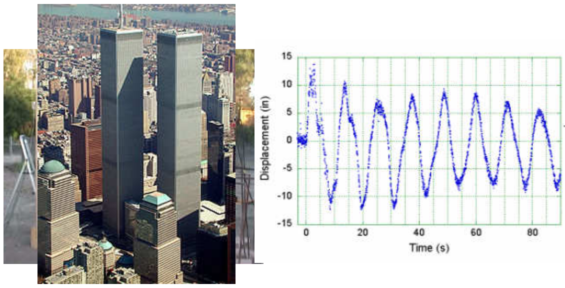
Monitoring Structural Response

Early warning based on "structural response" is not practical

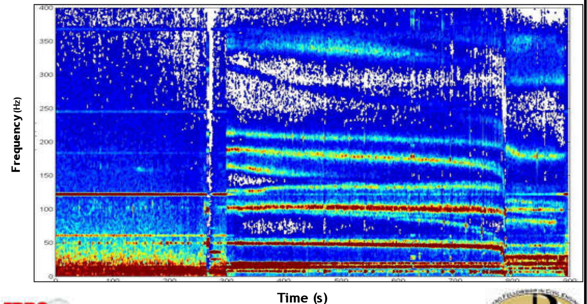
Practical Observations



Insights into Characteristic Behavior

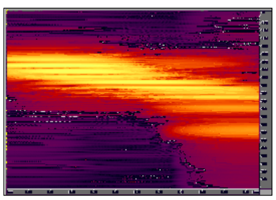


Beyond "Structural Resonance"

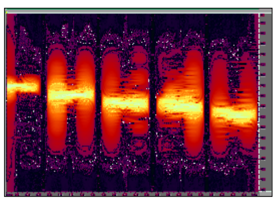


Audible Indicators

Structural spectrum is shifted into the audible range



Continuous sliding pitch



Discrete frequency blocks (chords)

Can we do better?

Wireless Fire-Sensor v2

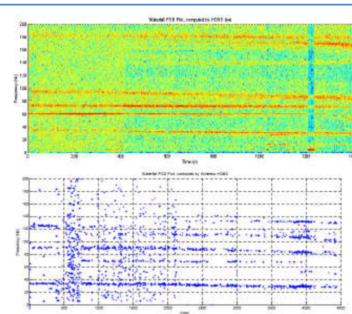
Hardware

- 50% reduction in Original PCB area
- Minimum 2 Hour battery life (estimated)
- Rechargeable Battery
- Optional MicroSD card storage
- One unit fully functional; three more in fabrication
- Wireless L.O.S range: 300ft; Extendable up to 1mile.
- 12-bit resolution over ±1.7g, 5kHz bandwidth; Extendable to 14-bit

Casing

- Preliminary casing designed and constructed
- One-handed design
- Bolt-mount for controlled testing scenarios
- Modular Accelerometer Design

Relative Accuracy Criteria?



Sensor – Most Critical

- Fire-induced vibrations can have low SNR
- Large civil structures typically produce signals with low SNR
  - A major obstacle to "health monitoring" in the 70's and 80's
  - Advances in instrumentation, computer, and manufacturing technologies in the 90's allows a different approach
- "Dense Instrumentation" can replace sophisticated algorithms and expensive instrumentation for health monitoring purposes
- Low-cost, high sensitivity (V/g), wide bandwidth, I/O

Next Steps

- Algorithm development could continue…
  - Probably not needed for practical field units
  - Wireless systems are being developed
- FEMA fire prevention and safety grant
  - BFRL
  - LA County Fire Department
  - Distribution of wireless systems
  - Database development

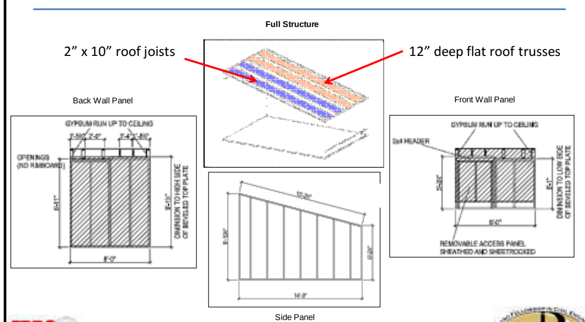
Acknowledgements

- **Phoenix Fire Department, Arizona**
- City of Phoenix Development Services Department
- Kinston Fire Department, North Carolina
- Dale City Volunteer Fire Department, Virginia
- Prince William County Department of Fire and Rescue, Virginia
- Bureau of Alcohol Tobacco and Firearms
- **Los Angeles County Fire Department, California**
- **Ventura County Fire Department, California**
- Fillmore City Volunteer Fire Department, California
- NIST
- Harvey Mudd College

WTCA Demonstration

- WTCA conducted demonstrations aimed at comparing truss performance during burn
  - against joist performance
    - two (identical) structures constructed
    - ½ roof joist and ½ roof truss support system
    - OSB (oriented stand board) ply around exterior and roof diaphragm
- Tests conducted at the Fire Service Training Bureau Facility (Ames, Iowa) August 25 & 26 2007

Construction Diagrams



Joist vs Truss Performance

- Demonstration designed to illustrate superior truss performance
- Performance criteria
  - Joist supports collapse first
  - Joist supports sag (first, significantly)
  - Truss supports loose strength gradually (vs suddenly)
  - Not clearly defined

Burn Test

Still Frame Replay

Still Frame Replay

Still Frame Replay

Still Frame Replay

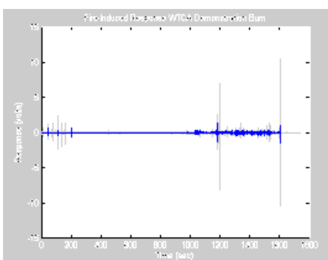
Still Frame Replay

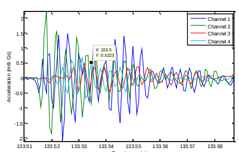
Monitoring Stability Loss in Burning Buildings
Zee Duron

Still Frame Replay

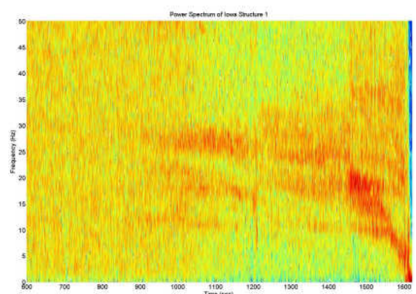
Still Frame Replay

Response Behavior

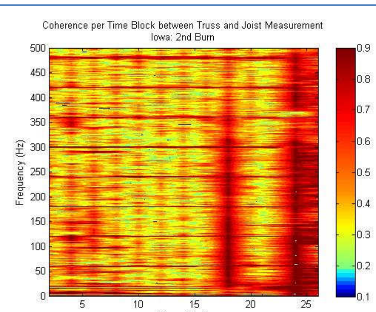




Spectral Response



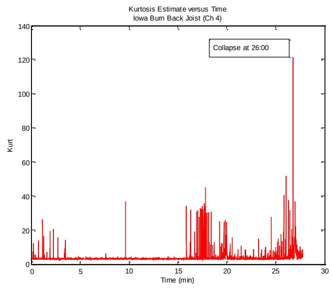
Coherence



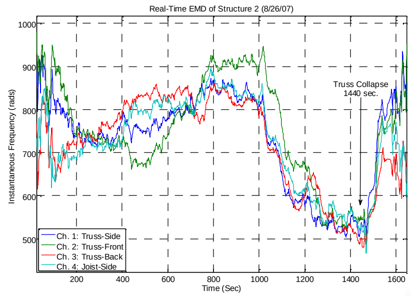
Stability Trackers

- Kurtosis –is a measure of the "peakedness" of the probability distribution of a real-valued random variable.
  - Higher kurtosis means more of the variance is due to infrequent extreme deviations, as opposed to frequent modestly-sized deviations.
- Mode Decomposition – (Huang et al. 1998) decomposes non-stationary and nonlinear signals into intrinsic mode functions (IMFs)
  - IMFs have well behaved Hilbert Transforms leading to instantaneous frequency calculations
- Impulse Counter – tracks the number and frequency of impulse (transient peaks) that occur
  - Simple indicator
- Instantaneous Frequency – tracks changes in frequency (smeared across bands)

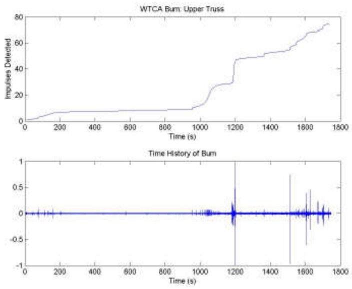
Kurtosis



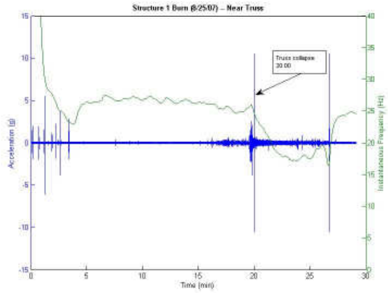
Mode Decomposition



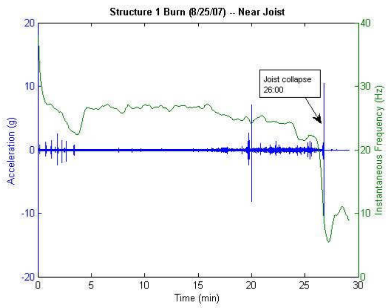
Impulse Counter



Inst Freq – Truss Response



Inst Freq – Joist Response



Findings/Recommendations

- Tests did not isolate joist from truss performance indicators
  - Structural coupling evident
  - Truss collapse occurred first (both tests)
    - Joists remained in place under load (both tests)
- Separate structures should be built
  - Test procedures need to be re-evaluated
  - Failure criteria need to be defined
  - Quantitative measurements are needed to assess performance

Monitoring Stability Loss in Burning Buildings
Zee Duron

Deliverables

- Prototype System
  - Fire Sensor (wired, wireless), HOBS
  - Instruction Manual
  - Training Materials
  - Delivery Date
    - Summer 2009
- Suggestions for future considerations
  - A gap exists between detailed numerical modeling efforts and practical field applications
  - Stability monitoring experiences indicate construction materials and type do not mask global characteristics
    - Expand field testing experience with structures
    - Develop numerical models that demonstrate observed behavior
      - Could lead to more understanding of how structural systems fail

Acknowledgements

- WTCA
  - KIRK GRUNDAHL, P.E.
- De Pietro Fellows
  - Leah Andersen
  - Vatche Attarian
  - Ben Traborsky
  - Zack Rubin
  - Zach Lupei
  - Casey Schilling

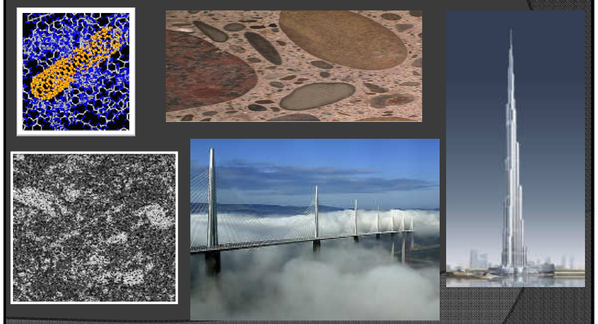
STRUCTURES SUBJECTED TO BLAST LOADING: PROTECTION, STABILIZATION AND REPAIR

Alexander Cheng, Ahmed Al-Ostaz and Chris Mullen

Nano Infrastructure Research Group
University of Mississippi

DHS Stabilization of Buildings Workshop
August 25-27, 2009

From Nanostructure to Infrastructure



Scientific Background

- During the last two decades, tremendous progress has been made in nanoscience
- New classes of nano materials, such as carbon nanotubes, nanowire, quantum dot, are being assembled, atom by atom, with different applications in mind—electronics, biomedicine, energy, environment
- However, these materials are still rare and quite expensive

Cont. Scientific Background

- For the protection of the nation's critical infrastructure, we need nano materials, that are *low cost* and in *huge quantity*
- Not all nano materials are man-made and expensive. There are many naturally occurring materials that are at or near nano size, such as nanoclay, volcanic and fly ash, and other minerals
- These materials are low cost and abundant in quantity for infrastructure protection

Ultimate Scientific Goal

- Design material physical principles: If we know how nano particles alter and improve upon material properties based on physical and mechanical laws, then we may be able to "design" infrastructure materials for the desirable performance, such as tensile strength, ductility, brittleness, energy dissipation, etc., required for different protection types (blast, impact, fire resistance, ...)

What is Engineering Design?

- Structural design: Given a material, we seek the most effective and efficient design to deliver the maximum performance. (We put the material where it is needed)
- Material design: When we reached the limit of structural design, we seek materials with better performance (at a cost)
- Design material: When existing materials cannot deliver the performance, we seek to design (new) materials

Mechanics Based Design

- Performance needed: Blast, impact, penetration, earthquake, fire, aging, corrosion, energy absorbing…
- Material properties: Tensile strength, hardness, ductility, brittleness, damping, viscoelastic, memory, rate dependent …
- Which material property delivers what performance?
- Answer these questions based on physical-mechanical laws

Are We There Yet?

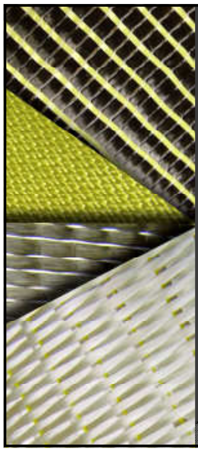
- Almost
- Recent advances are promising
- Knowledge gaps need to be filled
- Research needed

Gaps and Needs of Research

1. Use of advanced materials and repair technologies
2. Use of higher technologies (nano enhanced, bio inspired, self healing, …etc)
3. Add a second layer of vulnerability: fire, hurricanes, earthquake
4. Establishing a simplified air blast tools for quick calculations of range of explosives: retrofitting / performance based design.
5. Integrating advances in materials, damage assessment and evacuation procedures
6. Developing data base of failure scenarios using recent advances in computer modeling technologies.

1-Use of Advanced Materials and Repair Technologies

- Lightweight, rapidly deployable composites for shoring, pinning, bracing, and other temporary structural support purposes.
- FRP (fiber reinforced plastic/polymer) for strengthening damaged columns and beams
- Composite fixtures for strengthening column-beam connections
- Polymer concrete for rapid concrete repair
- Polymer sprays for strengthening walls and floors
- high-strength, fast-set grouts (shotcrete) for foundation and soil stabilization



FYFE Co. LLC
Tyfo® Fibrwrap® Systems

Two-Span Bridge Tested at University of Nevada, Reno

Edward R. Fyfe
August 2009

¼ Scale 2-Span-Bridge Tested at UNR

Highest Repairable Damage Level

Highest Repairable Damage Level

- Max Drift Ratio: 10.4%
- Max Longitudinal Bar Strain: 72000 με (30 times the yield strain)
- Max Spiral Strain: 1400 με (74% of yield)

Jacketing properties

FYFE Co. Tyfo® SCH-41 Fiber/Tyfo® S Epoxy System

- Design
  - E=8925 ksi
  - Tensile strength=100 ksi
  - Rupture strain=0.012
  - Laminate t = 0.04”
  - Design properties are based on one week regular curing.
- 54 hr cure (Actual)
  - E=8292 ksi
  - Tensile strength=89 ksi
  - Rupture strain=0.01
  - Laminate t = 0.04”
  - Actual properties are achieved after 54 hours curing.

Repair process

Repair Process Cont’d

Repair Process Cont’d

Curing

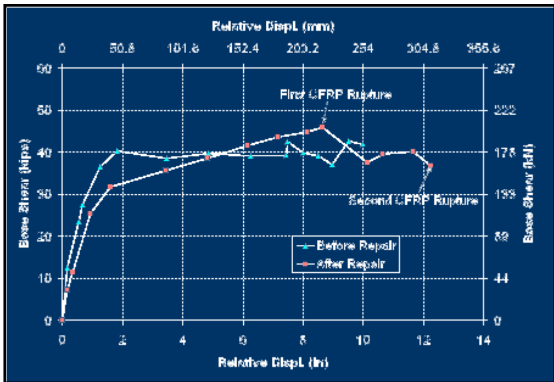
- 54 hours curing
  - 24 hours of elevated heat (94°F to 100°F) using 1000-watt lamps, heater, and an oscillating fan under the plastic sheet cover.
  - 30 hours of ambient lab temperature.
  - Specified curing is one week.

Drift Capacity of the Repaired Bent = 12.75%

Failure Mode

West column (Test-07)

East column (Test-11)



Repair Performance

- Original Bent-2
  - Max drift=10.4%
  - Service stiffness=31.65 kips/in
  - Strength=40.106 kips
- Repaired Bent-2
  - Max drift=12.75%
  - Service stiffness=27.43 kips/in
  - Strength=39.284 kips

2- Use of Higher Technologies

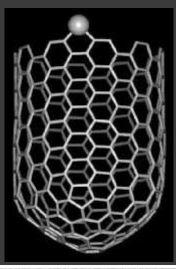
- Low-cost nano particle additives, such as nano clay, POSS, grapheme platelets, Tripoli, cellulose whiskers, etc. to enhance the structural performance of polymer concrete composites.
- Quasi-3D woven fabric for better performing FRP
- Nano particle additives, such as carbon Nanotubes and Graphene, for health monitoring purposes, by mixing with repair material or applying as a thin layer, to enhance electrical or electromagnetic sensing capabilities.
- Nanoenhanced / Bio inspired Materials (e.g. Sea shell like materials, self healing materials).

Nano Materials

Why the Interest in NanoComposites?

- ***PROPERTY ENHANCEMENT***
  - Mass Reduction (low density, low concentration)
  - Increased Stiffness (high aspect ratio)
  - Increased Toughness (engineered adhesion)
  - Improved Appearance (nano size, scratch and mar resistance).
  - Electrical Conductivity (electrostatic dissipation, electrostatic painting, electromagnetic shielding)
  - Thermal Conductivity, lower C.T.E., higher T**ult**
  - Reduced Flammability (less combustible material)
  - Barrier to Permeants (platelet)

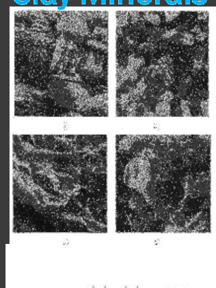
Carbon nanotube characteristics

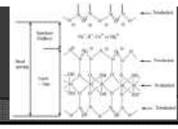


- Single-wall carbon nanotubes and multi-wall carbon nanotubes
- Diameter: ~ 1 *nm*
- Length: ~ 100 m*m* (and larger)
- Superior Mechanical Properties
  - Elastic Modulus: ~ 1 TPa
  - Density 1/6th of steel
  - Conductive ability is 100,000 times that of copper
  - Yield Strain: More than 4%
  - Buckling Strain: ~ 5% (aspect ratio of 1/6)

~ $100/g (Nanotube)
$80-100/lb (milled VGCF)
$40-50/lb (fibril VGCF)

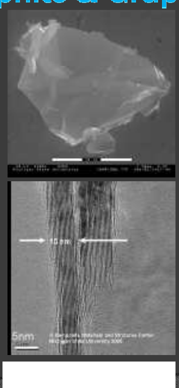
Clay Minerals characteristics





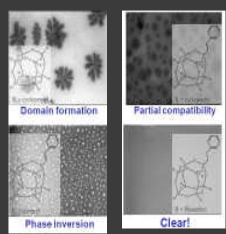
- Clay Minerals are hydrous aluminum phyllosilicates
- Have variable amount of iron magnesium alkali metals and other cations
- Typical MMT have net charges distributed within the octahedral layer or tetrahedral layer
- Bulk modulus ~ 20-50 Gpa
- Young's Modulus 6.2 GPa

Graphite & Graphene Characteristics

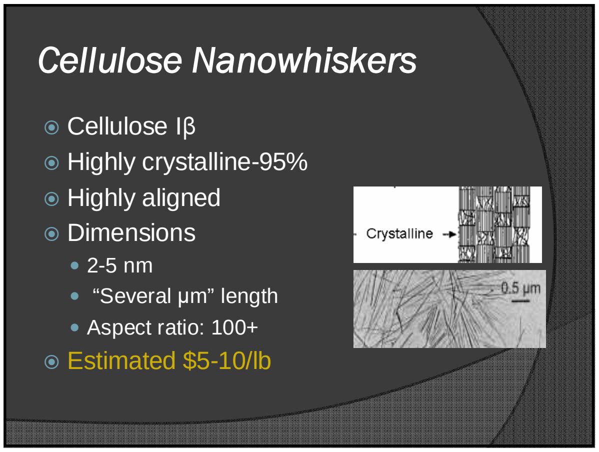


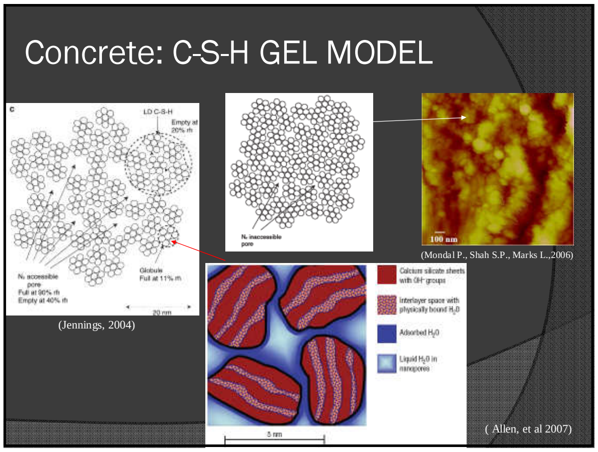
- Single carbon Layer and multi carbon Layers
- Thickness: ~ 5-10 *nm*
- Length: ~ .86-15 m*m* (and larger)
- Superior Mechanical Properties
  - Elastic Modulus: ~ 1 TPa
  - Intrinsic Strength ~ 130 GPa (Experiments conducted for a monolayer graphene by Lee at .el. 2008, reported that graphene is strongest material ever measured)

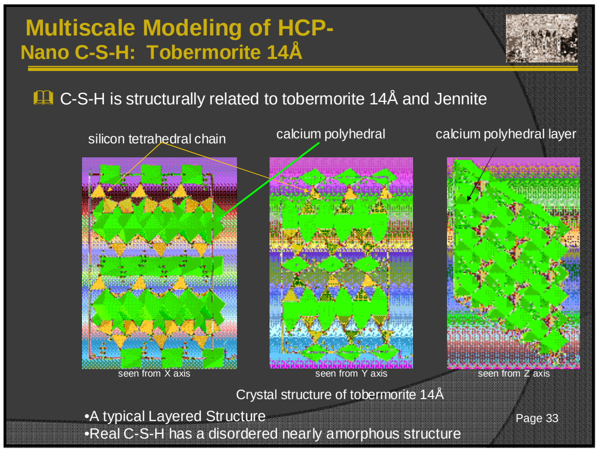
POSS Organic- Inorganic Characteristics

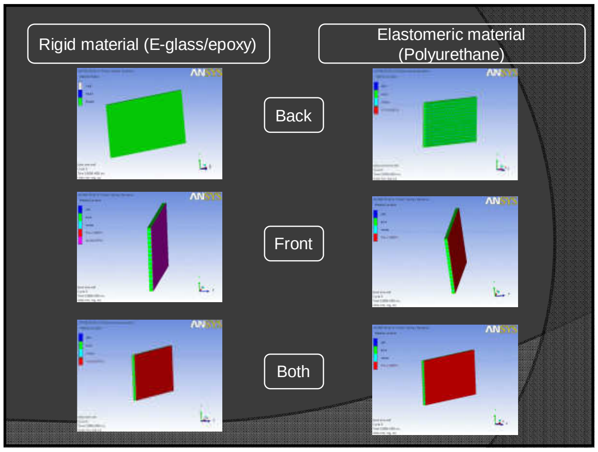


- A new class if organic –inorganic nanocomposites containing POSS monomers which have been copolymerized with organic monomers
- POSS hybrid chemical composition
- POSS molecules span 1~3 nm size range
- Improve impact resistance
- Reduce friction and improve flow
- POSS can dissolve in polymers

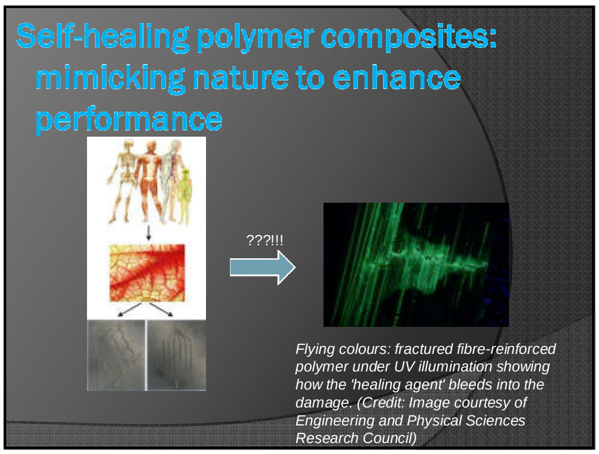

Cellulose Nanowhiskers
Cellulose Iβ
Highly crystalline-95%
Highly aligned
Dimensions
2-5 nm
"Several μm" length
Aspect ratio: 100+
Estimated $5-10/lb
Crystalline
0.5 μm


Concrete: C-S-H GEL MODEL
(Jennings, 2004)
(Mondal P., Shah S.P., Marks L.,2006)
100 nm
Calcium silicate sheets with OH⁻ groups
Interlayer space with physically bound H₂0
Adsorbed H₂0
Liquid H₂0 in nanopores
5 nm
(Allen, et al 2007)


Multiscale Modeling of HCP-
Nano C-S-H: Tobermorite 14Å
C-S-H is structurally related to tobermorite 14Å and Jennite
silicon tetrahedral chain
calcium polyhedral
calcium polyhedral layer
seen from X axis
seen from Y axis
seen from Z axis
Crystal structure of tobermorite 14Å
•A typical Layered Structure
•Real C-S-H has a disordered nearly amorphous structure
Page 33


Rigid material (E-glass/epoxy)
Elastomeric material (Polyurethane)
Back
Front
Both


Natural Nanocomposites: See-shells (Nacre-Mother of Pearl)
What is the secret recipe that mother nature uses to fabricate see-shells?
What roles do the nanoscale structure play in the inelasticity and toughness of see shells?
Can we produce see-shell like materials?
(a) Schematic of micro-architecture of nacre (b) AFM of fractured surface © SEM of fractured surface showing brick and mortar structure
Atomic force microscopy images of (a) crack deflection, (b) crack extrusion, © particles squeezed out at the platelet interface (d) slip bands and separation at the platelet interface, indicated by arrows (e) SEM of nanoscale asperites on the aragonite surface (f) the organic polymer that serves as adhesive to hold the platelets together as indicated by the arrow.
Rotation and deformation of nanoparticles in nacre platelet during three point bending
X. Li, JOM: Mar 2007; 59(3);pg.71


Self-healing polymer composites: mimicking nature to enhance performance
???!!!
Flying colours: fractured fibre-reinforced polymer under UV illumination showing how the 'healing agent' bleeds into the damage. (Credit: Image courtesy of Engineering and Physical Sciences Research Council)

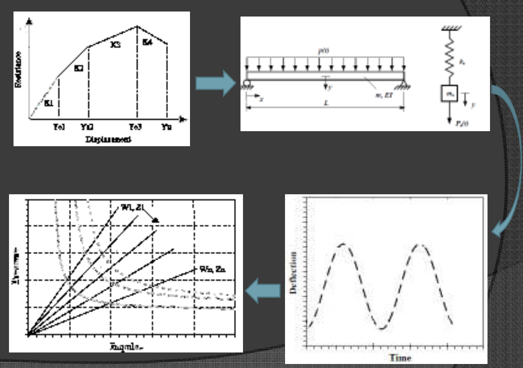
Biomimetic self-healing inspiration in advanced composite structures

Biological attribute	Composite/ Polymer Engineering	Biomimetic self-healing or repair strategy	Reference
'Concept of self-healing'	Remendable Polymers	Bioinspired healing requiring external intervention to initiate repair	Chen *et al*, 2002; Chen et al, 2003; Hayes et al, 2005
Bleeding	Capsules	Action of bleeding from a storage medium housed within the structure. 2-phase polymeric cure process rather than enzyme 'waterfall' reaction	White *et al*., 2001; *Kessler & White, 2001; Kessler et al., 2002*
	Hollow fibers	Action of bleeding from a storage medium housed within the structure. 2-phase polymeric cure process rather than enzyme 'waterfall' reaction	Bleay *et al*, 2001; *Pang & Bond, 2005a; Pang & Bond, 2005b; Trask et al, 2006*
Blood Cells	Nano particles	Artificial cells that deposit nano-particles into regions of damage	Lee *et al*, 2004; Verberg *et al*, 2006
Blood Flow Vascular Network	Hollow fibres	2D or 3D network would permit the healing agent to be replenished and renewed during the life of the structure	Toohey *et al*, 2006; Williams *et al*, 2006

Biomimetic self-healing inspiration in advanced composite structures- cont…

Biological attribute	Composite/ Polymer Engineering	Biomimetic self-healing or repair strategy	Reference
Blood Clotting	Healing resin	Synthetic self-healing resin systems designed to clot locally to the damage site. Remote from the damage site clotting is inhibited and the network remains flowing.	-
Skeleton/Bone healing	Reinforcing fibers	Deposition, resorption, and remodelling of fractured reinforcing fibers	-
Elastic/plastic behavior in reinforcing fibers	Reinforcing fibers	Repair strategy, similar to byssal thread, where repeated breaking and reforming of sacrificial bonds ca occur for multiple loading cycles	-
Tree bark healing – compartmentalisatio n	-	Formation of internal impervious boundary walls to protect the damaged structure from environmental attack	-

3- Establishing a Simplified Air-Blast Tools for Quick Calculations of Range of Explosives: Retrofitting / performance Based Design



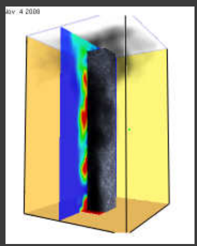
4- Add A second Layer of Vulnerability: Fire, Hurricanes, Earthquake…..

Example: Fire

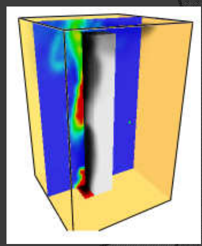
- Establish an approximate relationship between viscosity and temperature using geometry on the polymeric nanocomposite and on its thermally degraded melt
- Use the Particle Finite Element Model to investigate the time to mechanical weakening of the coating and the flow behavior under fire conditions, given the thermal characteristics and the geometry of the coating and the underlying steel
- Investigate how the structure (e.g., size and chemical functionality) and degree of exfoliation of the GO nano-flame retardants affects the rate of volatile fuel formation by performing simulated thermal degradation experiments using the NIST Reactive Molecular Dynamics (RMD) code.

Fire Simulation Temperature Profile

- Steel Column

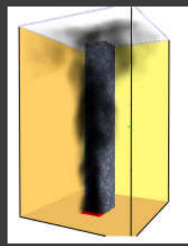


- Insulated Steel Column

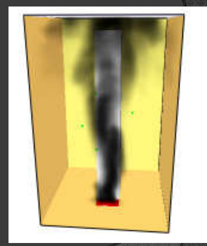


Fire Simulation Soot Profile

- Steel Column

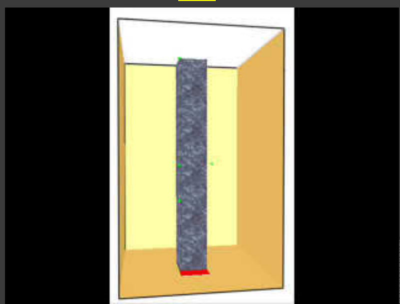


- Insulated Steel Column



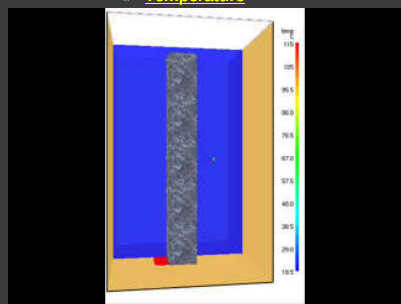
Smoke View Steel

- Soot



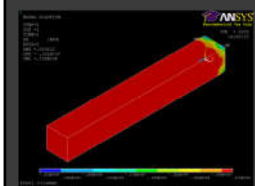
Smoke View Steel

- Temperature

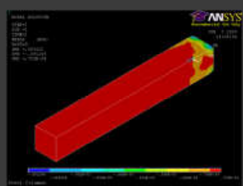


Thermocoupling FEM ANSYS

- Steel Stress $_{xx}$



- Steel Strain $_{xx}$



5- Integrating advances in materials, damage assessment and evacuation procedures

E-Sim

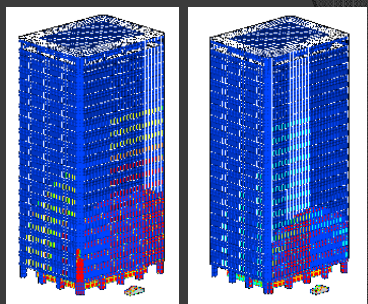
- To provide an animated, graphical means of evaluating and quantifying the impact on human egress/safety from nano-particle reinforced composites when a building is exposed to a blast load

Building Background

- Nineteen Floor Office Building with Unprotected Parking Below
- Contains High-profile State Government Officials
- Also Contains Offices for Other Important State-run Organizations

Blast Analysis

- Blast Model Generated to View Areas Sustaining Significant Damage During Unprotected & Protected Explosive Events
  - Typical 8"-Thick CMU Building Construction
  - Includes Glazing
  - Protected with 5mm Nylon 6,6-XGnP Nano-composites
- Blast Model Created Using ***AT-Assessor***
- Blast Loads Applied to E-Sim Model for Scenarios 2 & 3

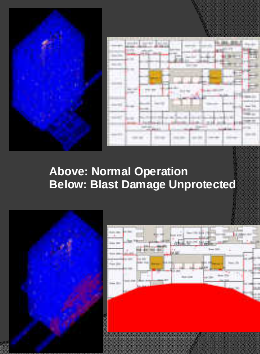


Unprotected Facility

Protected Facility w/ Window Upgrades

Task 2: Scenario Simulations

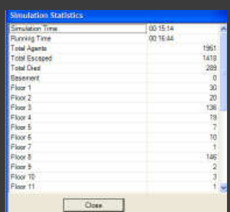
- Scenario 1: Undamaged Building Under Normal Operation
- Scenario 2: Building Damaged by Blast without Nano-Particle Composites
- Scenario 3: Building Damaged by Blast with Nano-Particle Composites



Above: Normal Operation
Below: Blast Damage Unprotected

Multi-Scenario Simulations

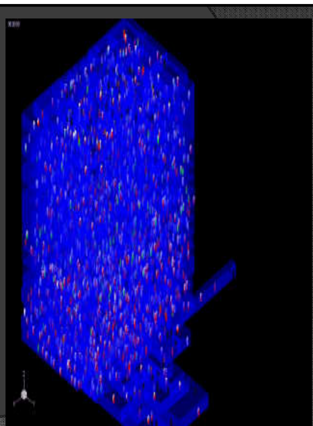
Scenario 3: Nano-Reinforced Structure Subject to Damage



Simulation Statistics

Simulation Time	00:15:14
Running Time	00:16:44
Total Agents	1961
Total Escaped	1418
Total Died	289
Basement	0
Floor 1	30
Floor 2	20
Floor 3	138
Floor 4	19
Floor 5	7
Floor 6	10
Floor 7	1
Floor 8	146
Floor 9	2
Floor 10	3
Floor 11	1

Close



6- Developing data base of potential progressive failure scenarios using recent advances in computer modeling technologies.

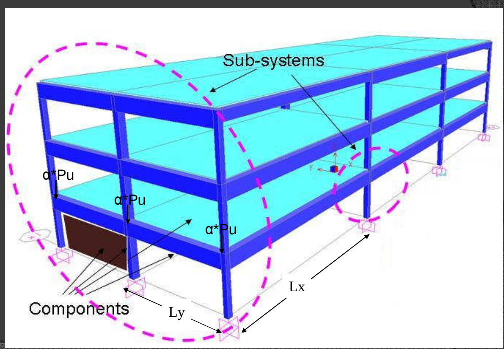
- Differentiation of rescue operations types and building structure destruction levels
- Be applicable to a variety of commercial and industrial building construction having, for example, steel or concrete moment frames or concrete or masonry shear wall systems
- Mechanics based material damage models for all critical load carrying heterogeneous structural components

- Computational algorithms for implementing the material damage models in finite element codes
- Coupling laws that integrate the damage models to overall strength and stiffness of the components
- Computational methodologies that predict residual strength and stiffness of damaged critical components based on material as well as structural degradation
- Physics based envelope of critical failure criteria for individual structural component of the overall structure to enable prediction of survivability, reparability, collapse or destruction of the system.

Static Model

- Live loads and spans are important parameters governing the preliminary design of a structure.
- At the member level, local vulnerabilities need to be identified in order to map the blast damage on the structure
- The fiber model allows tracking of damage states in the concrete and rebar at points defined on the section
- The collapse resistance of the damaged structure is analyzed by removal of severely damaged columns along the long axis of the building and studying the nonlinear static response of the structure

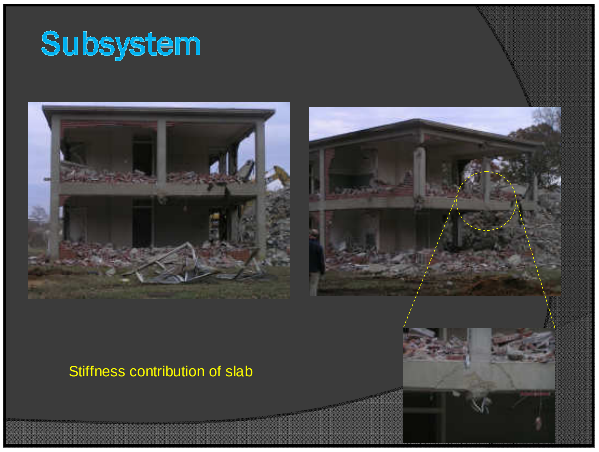
Typical Low Rise Structure



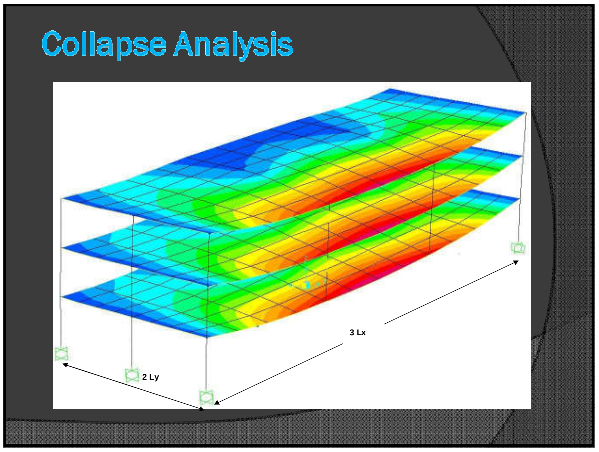
Typical Low Rise Structure

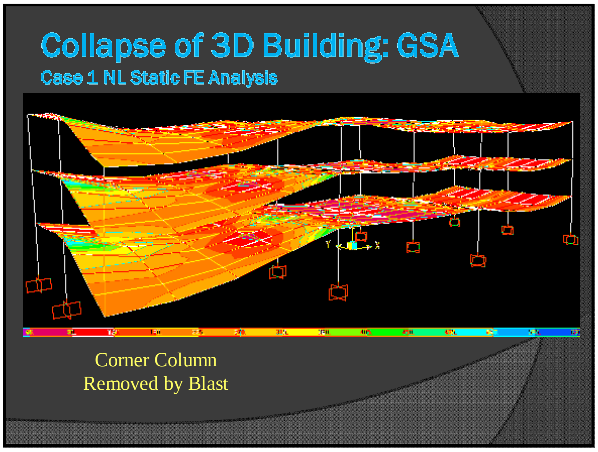
Subsystem

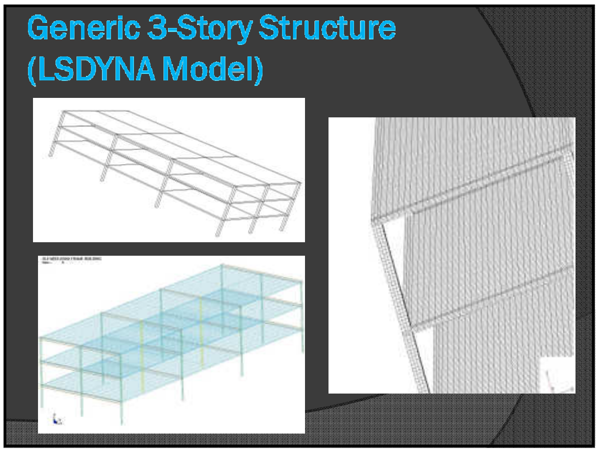
Subsystem

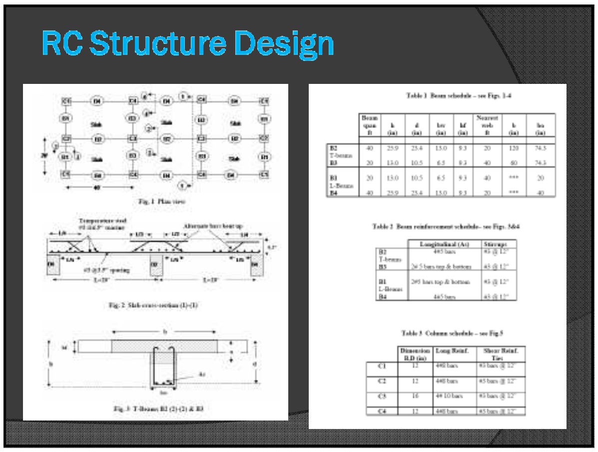

Subsystem
Stiffness contribution of slab

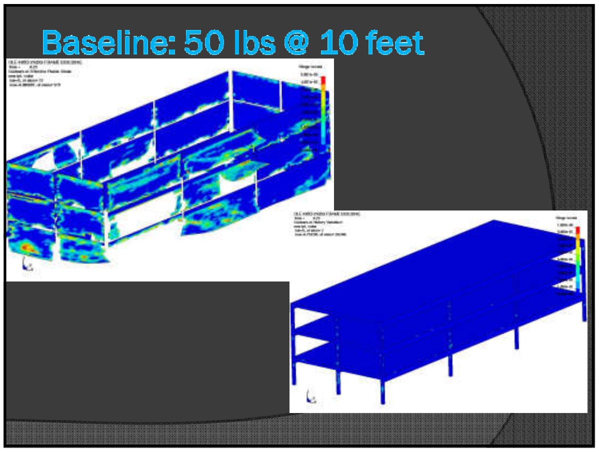

Subsystem

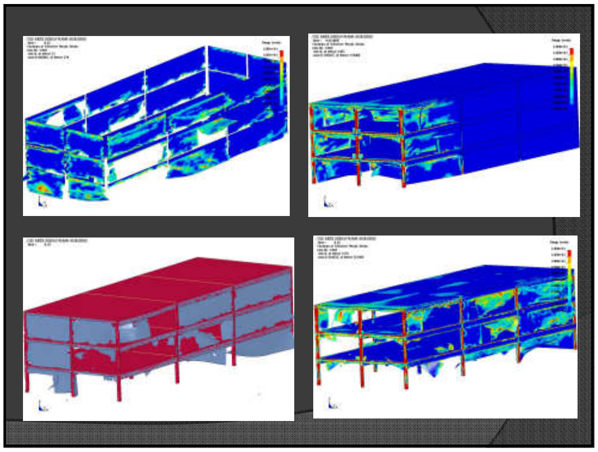

Collapse Analysis
3 Lx
2 Ly

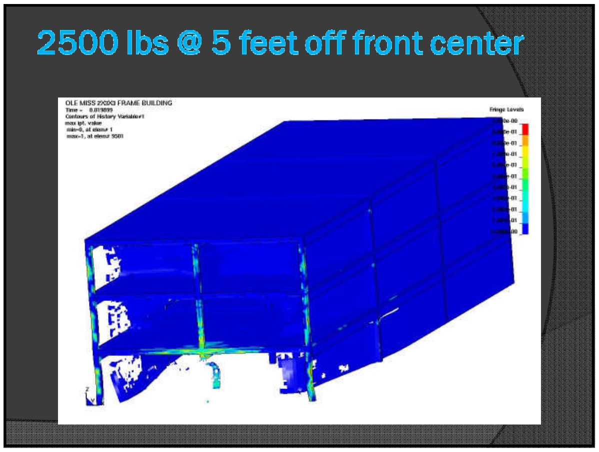

Collapse of 3D Building: GSA
Case 1 NL Static FE Analysis
Corner Column
Removed by Blast


Generic 3-Story Structure
(LSDYNA Model)


RC Structure Design


Baseline: 50 lbs @ 10 feet




2500 lbs @ 5 feet off front center

Monitoring Strategies for Rapid Assessment of Structural Condition and Stability Following a Terrorist Event

Andrew Zimmerman and Jerome Lynch

Monitoring Strategies for Rapid Assessment of Structural Condition and Stability Following a Terrorist Event

Andrew T. Zimmerman & Jerome P. Lynch
Department of Civil and Environmental Engineering
Department of Electrical Engineering and Computer Science
University of Michigan, Ann Arbor MI

DHS Stabilization of Buildings Workshop
Vicksburg, Mississippi
August 25-27, 2009

Outline

- Introduction and motivation:
  - Blast loads on structures
- Trends in sensors and sensing systems:
  - Emergence of new sensor types
  - Monitoring systems
- Sensing needs for condition assessment
- High density wireless sensor networking:
  - Wireless sensor networks
  - Embedded computing
- Cyberinfrastructure for unification of measurements and simulations
- Conclusions

Motivation

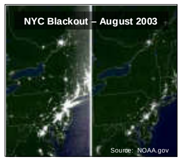
- Civil infrastructure upon which society depends:
  - Buildings
  - Bridges
  - Maritime ports
  - Electrical grids
- Vulnerabilities exist placing civil infrastructure in peril:
  - Normal wear and tear
  - Natural catastrophe
  - Terrorist activities

Motivation

- Vulnerabilities exist placing civil infrastructure in peril:
  - Normal wear and tear
  - Natural catastrophe
  - Terrorist activities

Identify design flaws

Detect system degradation



Remediate systems after failure

Terrorist Activities

- Terrorist activity remains a challenging risks to design for:
  - Difficult to predict *a priori* where and when a terrorist explosion will occur
  - Quantification of exact risk is a challenging problem
  - Must balancing risk against the cost of hardening structures
- Terrorism likely to be a more commonplace issue in the future


Collapse of the Alfred P. Murrah Federal Building
Oklahoma City, Oklahoma (April 2005)


World Trade Center in ruins
New York, New York (September 2001)

Outline

- Introduction and motivation:
  - Blast loads on structures
- Trends in sensors and sensing systems:
  - Emergence of new sensor types
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  - Wireless sensor networks
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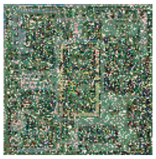
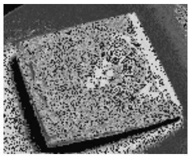
Monitoring Strategies for Rapid Assessment of Structural Condition and Stability Following a Terrorist Event

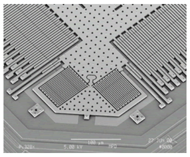
Andrew Zimmerman and Jerome Lynch

Emergence of New Sensors

- Explosive growth in sensing technology over the past two decades:
  - 1980's – emergence of microelectromechanical systems (MEMS)
  - 1990's – rapid advancements in data acquisition and telemetry technologies
  - 2000's – nanotechnology creating multifunctional materials
- MEMS offers compact and low-cost sensors:
  - Leverage IC manufacturing to batch fabricate sensors at low cost
  - Collocation of computing and sensing on a single chip

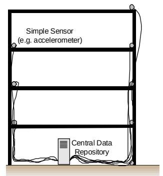

Sensor with circuitry


MEMS gyroscope (Shkel et a. 2005)

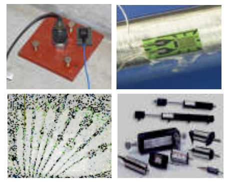

MEMS accelerometer (Analog 2004)

Structural Monitoring Systems

- Structural monitoring systems employed for "critical" structures:
  - Employ sensors measuring structural responses (*e.g.* accelerometers)
  - Sensors are "wired" to a central repository using extensive wiring
  - Suffer from high installation costs:
    - Approx. $3,000 (US) per channel to install in buildings



Cable-based structural monitoring system


Typical sensors employed for structural monitoring

Rapid Assessment of Structural Condition and Stability Following a Terrorist Event
DHS Stabilization of Buildings Workshop, Vicksburg, Mississippi, August 25-27, 2009
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Examples of Monitoring Systems

- Structures world-wide are instrumented with monitoring systems:
  - Empirical response data of structural responses to seismic and wind loads
  - Model calibration using structural response data is typical


Golden Gate, CA (76 channels)


Vincent Thomas, CA (26 channels)


Transamerica Building,CA (18 channels)


Tsing Ma Bridge, HK (+300 channels)


Pacoima Dam, CA (20 channels)

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Structural Health Monitoring

- Structural health monitoring (SHM) systems have also been proposed by the structural engineering community :
  - Differ from traditional structural monitoring systems
  - Automate the processing of response data to detect deterioration/damage
  - Technology is still under development in academia and industry
- The benefits of SHM are enormous:
  - Condition-based maintenance in lieu of schedule-based methods
  - Real-time assessment of structural health can render structures safer

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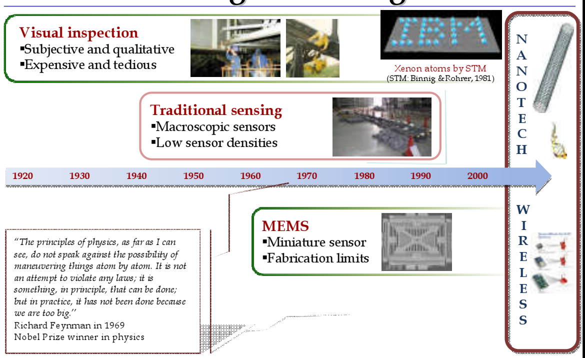
Sensing Technologies



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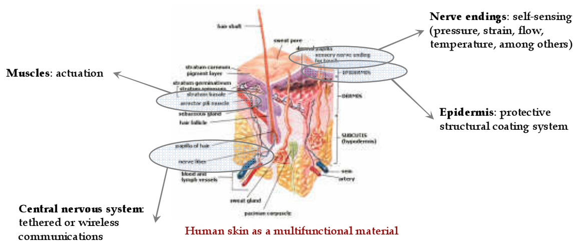
Biomimetic Multifunctional Materials

- Design of biomimetic multifunctional materials
  - Component-based damage detection paradigm
  - Self-sensing, actuation, energy harvesting, self-healing, among others



Human skin as a multifunctional material

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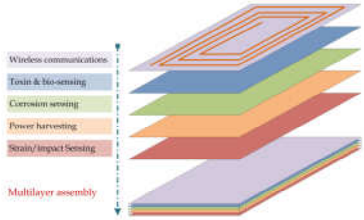
Multifunctional Sensing Transducers

- Biomimetic multifunctional active coating systems:
  - Layer-by-layer permits 2.5-dimensional nano- and macro-structuring
  - Micro- and nano-fabrication patterning techniques
  - Integrate with existing structural coating systems
  - Combine with nano- and micro-lithography techniques



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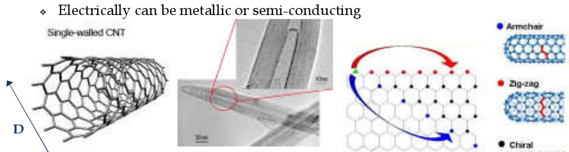
Carbon Nanotubes

- Single-walled carbon nanotubes (SWNT):
  - Rolled cylindrical structures with C atoms double-bonded (C=C)
  - Oriented hexagonally on the surface
  - Diameter (D): 0.4 ~ 10.0 nm
  - Impressive mechanical strength: ~200 times stronger (σ_T), 5 times stiffer (E) than steel
  - High aspect ratio (10^4 ~ 10^6) for scaffolding
  - Electrically can be metallic or semi-conducting



Tunneling electron microscope image of a multi-walled carbon nanotube
(Saito & Dresselhaus, 1998) *MIT*

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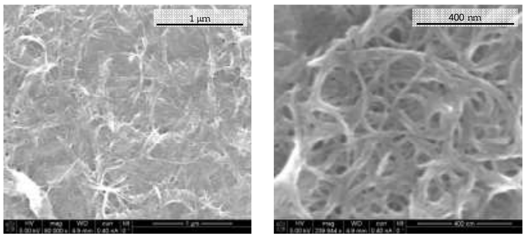
Nanocomposite Morphology

- Electrical conductivity and sensing based on percolated thin film morphology
  - Seek homogeneous composite with similar properties across entire film



Scanning electron microscopic (SEM) views of a 25 bilayer SWNT-PSS/PVA thin film
(Loh, *et al.*, 2008) *University of Michigan*

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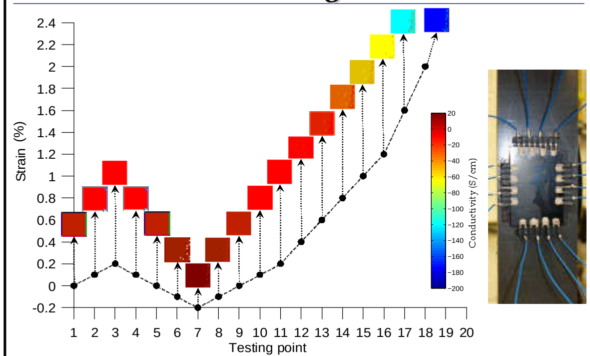
Skin Strain Sensing Performance



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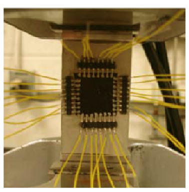
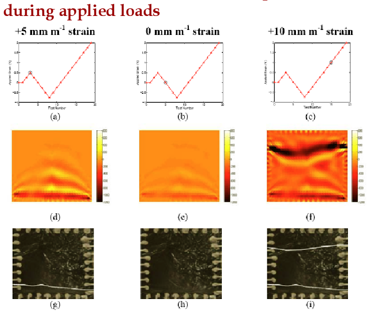
Spatial Micro-Cracking Identification

- Free-standing sensing skins affixed onto cementitious composites to identify micro-cracking during applied loads



Sensing skin epoxy-mounted onto cementitious composite surfaces



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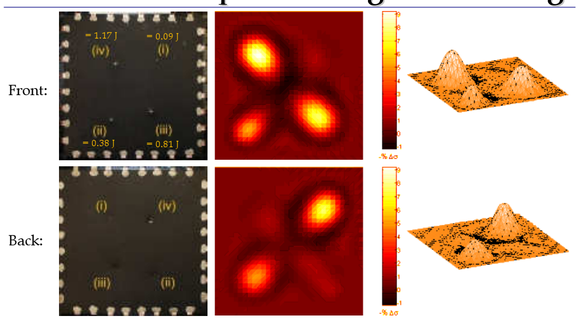
Distributed Impact Damage Monitoring



- Varied initial impact energy across four different structural locations
  - Performed EIT spatial conductivity reconstruction on both sides of the plate

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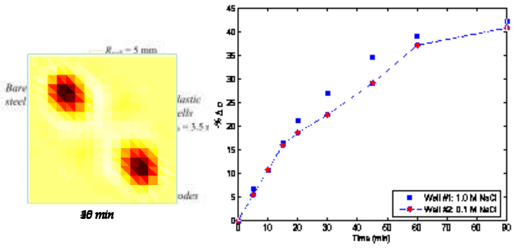
Spatial Corrosion Monitoring

- **Deposit corrosion-sensitive skins onto steel plates**
  - Exposed steel plates to salt (NaCl) solutions to accelerate corrosion
  - Sensing skin detects severity of corrosion and rust formation



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Outline

- Introduction and motivation:
  - Blast loads on structures
- Trends in sensors and sensing systems:
  - Emergence of new sensor types
  - Monitoring systems
- **Sensing needs for condition assessment**
- High density wireless sensor networking:
  - Wireless sensor networks
  - Embedded computing
- Cyberinfrastructure for unification of measurements and simulations
- Conclusions

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Sensors for Condition Assessment

- **Sensors for infrastructure monitoring during and after a terrorist event can be divided into three broad categories:**
  - Sensors for structural assessment
  - Sensors to monitor fire conditions (*e.g.*, temperature and gases)
  - Sensors to identify and track inhabitants

Stability Fire Rescue

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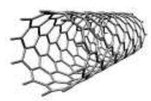
Sensors for Structural Assessment

- **The global and local behavior of a structure must be sensed:**
  - Predict stability and structural condition (damaged versus undamaged).
- **Many sensors exist for monitoring structural responses:**
  - Very few of these sensors would be operable at elevated temperatures
  - Sensors must also survive shock loads (for example, MEMS are too delicate)
- **Novel approaches for sensors resistant to shock and high thermal loads:**
  - Hardened packaging to allow sensors to withstand extreme environment
  - New sensor materials suited for high-thermal environments:
    - Ceramic and carbon materials for sensor construction



Carbon nanotubes can withstand extremely high temperatures

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Sensors to Monitor Fire Conditions

- **Sensors that can determine the existence and movement of fire:**
  - Help in assessing fire induced changes in the structure
  - Can assist in managing emergency response personnel entering the structure
- **Sensors for fire monitoring:**
  - Temperature sensors to measure ambient and component temperatures
  - Gas sensors that can sense gaseous molecules (*e.g.*, CO, CO2)
- **Sensors currently exist for measurement of temperature and gases**
  - Expensive, bulky and lack sensitivity
- **Opportunities exist to:**
  - Enhance the sensitivity of fire-based sensors (*e.g.*, gas sensors)
  - Miniaturize them through the use of MEMS and nanotechnology
  - Reduce their fabrication costs

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Sensors to Identify and Track Inhabitants

- **Tracking structural inhabitants is the first step towards evacuating them from a structure:**
  - Sensors are needed to monitor movement along egress paths
  - Identify incapacitated inhabitants that need assistance
  - Track emergency response personnel
- **Specific transducers to consider:**
  - Cameras and optical motion sensors
  - RFID/wireless technology
  - Again, hardening these sensors is necessary

Search and rescue inside a burning building requires tracking

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Andrew Zimmerman and Jerome Lynch

Outline

- Introduction and motivation:
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  - Monitoring systems
- Sensing needs for condition assessment
- **High density wireless sensor networking:**
  - Wireless sensor networks
  - Embedded computing
- **Cyberinfrastructure for unification of measurements and simulations**
- Conclusions

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Data Acquisition

- **Emergence of new sensor technologies is a double-edge sword:**
  - Low cost sensors is driving densities high (great!)
  - However, complexity must be better managed (challenging!)
    - Installation complexity
    - Data management complexity
- **Wireless sensor networks have emerged as a viable substitute to traditional tethered monitoring systems:**
  - Eradication of cabling keeps the cost of telemetry low
  - Advantage of wireless sensors is their ad-hoc communications

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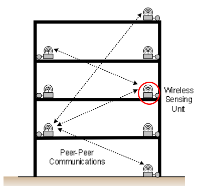
Wireless Structural Monitoring

- **Three innovations associated with wireless sensors:**
  1. Wireless communication - peer-to-peer and ad-hoc communication
  2. Cost – low cost nodes drives higher densities of sensors
  3. Computing - collocation of computing facilitates sensor-based interrogation



Wireless structural monitoring system

Numerous wireless sensor platforms

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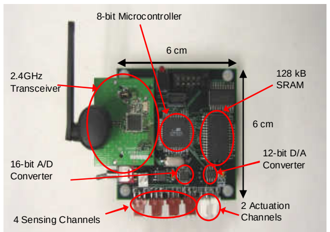
Wireless Sensor Prototype

- **Compact wireless sensor prototype:**
  - 16-bit ADC resolution on 4 channels
  - Enhanced range 802.15.4 radio (300 m)
  - Integration of 12-bit actuation interface



Completed Wireless Sensor Network

SPECIFICATIONS	
Cost	$175 per unit
Form Factor	5 cm x 6 cm x 2 cm
Energy Source	5 AA Batteries
Power	40 mA @ 5V
Range	300 m
Data Rate	250 Kbps
Sample Rate	100 kHz

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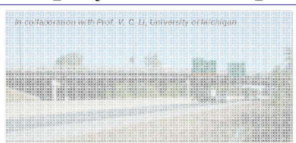
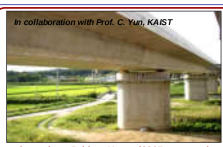
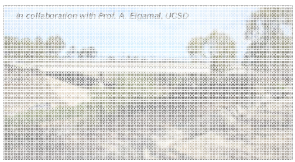
Deployments to Operational Structures



Grove Street Bridge, Ypsilanti, Michigan (2005)
18 wireless sensors measuring acceleration and displacement



Geumdang Bridge, Korea (2005 - present)
16 wireless sensors measuring acceleration



Voigt Bridge, San Diego, California (2006)
20 wireless sensors measuring acceleration

Wu Yuan Bridge, China (2005 - present)
8 wireless sensors measuring acceleration

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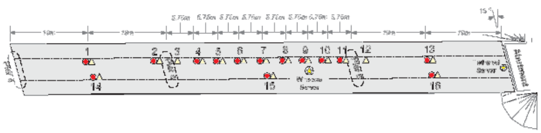
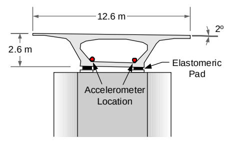
Instrumentation Strategy



Accelerometers for Structural Monitoring

Sensor Property	PCB393* Piezoelectric (Cable System)	PCB3801 MEMS Capacitive (Wireless System)
Range	± 1 g	± 3 g
Sensitivity	10 V/g	0.7 V/g
Bandwidth	2000 Hz	80 Hz
RMS Noise Floor	20 μg	0.5 mg
Dynamic Range	111 dB	95 dB

*** Amplified by a factor of 10**



SECTION A-A

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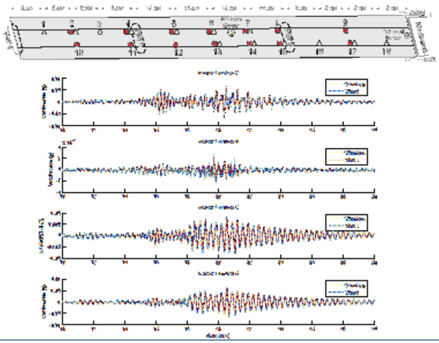
Forced Dynamic Response to Trucks



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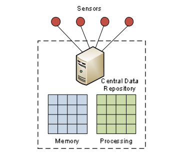
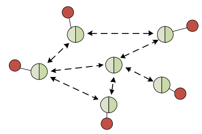
In-Network Data Processing

- **What sets wireless sensors apart is embedded computing at the sensor:**
  - Each sensing node has independent memory and processing cores.
  - However, each node is individually much less powerful than a modern PC.
  - Energy-efficient to interrogate data at the sensor than communicate raw data.
- **Scalable implementation must embrace distributed computing:**
  - Minimize communication to save energy and minimize data loss.
  - Parallel computing to offer speed and scalability to high nodal counts.



Tethered structural monitoring system



Wireless structural monitoring system

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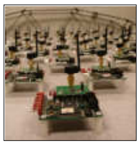
Why In-Network Processing?

- **What sets wireless sensors apart is embedded computing at the sensor:**
- **System scalability:**
  - Streaming raw data is not scalable since it would exhaust bandwidth.
  - Higher communication demand erodes the wireless channel performance.
- **Power management:**
  - Communication is power-intensive - critical issue for battery powered nodes.
- **Data management:**
  - Avoidance of data inundation at the central repository.



Dense wireless sensor networks

Demand for power efficiency

Avoidance of data inundation

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Distributed Computing Platform

- **Wireless sensor networks are a very unique computing platform:**
  - Small memory and computing footprint at each sensor node
  - Significant memory and data processing ability within the network
  - Advantages include reduction of data glut and system power efficiencies

Embedded Wireless Sensor Software Library for Structural Health Monitoring

Embedded Algorithm	Embedded Application
Fast Fourier Transform	Modal analysis
Peak picking algorithm	Mode shape determination
Frequency domain decomp.	Mode shape determination
AR, ARMA, ARX time series	Structural health monitoring
Bayesian classifiers	Structural health monitoring
State-space control	Structural control
Cable tension force estimation	System identification
Simulated annealing	Parallel model updating

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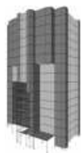
Model Updating

- **Impossible to directly sense the properties of every facet of the system:**
  - Analytical models predict the response of the system
  - Models must be "updated" so as to represent the true behavior of the system
  - Well calibrated models are a powerful element of the larger SHM strategy:
    - Changes in system properties could indicate damage
- **Model updating is a challenging combinatorial optimization problem**

Actual Structure



FEM Model Representation

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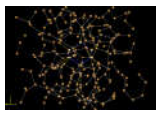
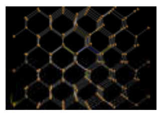
Combinatorial Optimization

- **Combinatorial optimization (CO):**
  - Minimization (maximization) of objective function with a large state space
  - Very difficult to solve computationally in a reasonable amount of time
  - Approximate solution found in a short time period is more ideal
- **Annealing of metals is a natural combinatorial optimization problem:**
  - Annealing a metal cools a metal from a high temperature
  - Atoms are perturbed from their initial position and wander randomly
  - Atoms are "searching" for a configuration of a lower internal potential energy
  - Metropolis *et al.* (1953) modeled the annealing process in a computer



Random Atomic Configuration



Ordered Atomic Configuration

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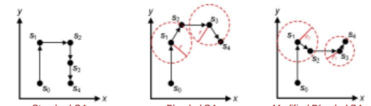
Simulated Annealing

- **Simulated annealing inspired by metallurgy to solve CO problems:**
  - Minimize an objective function: $E(s) = |x_{sensed} - x_{analytical}|$
  - Randomly select model states, s_{new}, until E is minimized
  - Introduce the concept of annealing through temperature, T
- **Annealing process:**
  - Metropolis Criterion accepts new energy state if and only if:
    - $E(s_{new}) \le E(s_{old}) - T\ln(U)$, where U is a random number $(0 < U < 1)$
  - Allows an "uphill" state selection to prevent convergence to local minima
  - As T reduces during annealing, state selection tends increasingly "downhill"



Standard SA (Metropolis and Hastings) | Blended SA (Levin and Lieven) | Modified Blended SA (Zimmerman and Lynch)

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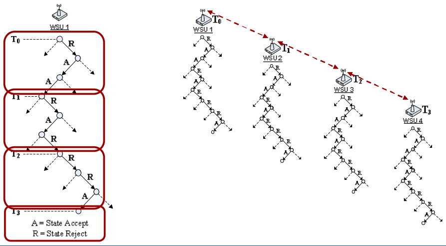
Wireless Parallel Simulated Annealing

- **Embed simulated annealing in wireless sensor for model updating:**
  - Computationally exhaustive for a single wireless sensing unit
  - Computational demand is associated with the calculation of E
  - Solution is to parallelize the calculation of E by splitting search tasks



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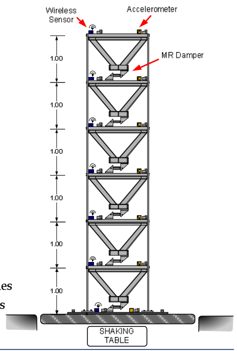
Experimental Testbed

- **6 Story Steel Structure:**
  - NCREE, Taipei, Taiwan (with Prof. C. H. Loh)
  - MR dampers installed at each floor
  - Each floor instrumented with an accelerometer
  - Seismic base excitation
- **Wireless monitoring system installed:**
  - Wireless sensor upon each floor
  - Accelerometer upon each floor
- **Model update to detect changes in damping:**
  - Lumped mass shear structure model assumed
  - Change structural properties using MR dampers
  - Embedded modal estimation:
    - Peak picking provides modal frequency
    - Frequency domain decomposition give modes
    - Random decrement provides damping ratios
  - Perform model update using multiple sensors



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Experimental Testbed

Test structure on shake table

Wireless sensor on 4th floor

MR damper and LVDT on 2nd floor

MEMS accelerometer

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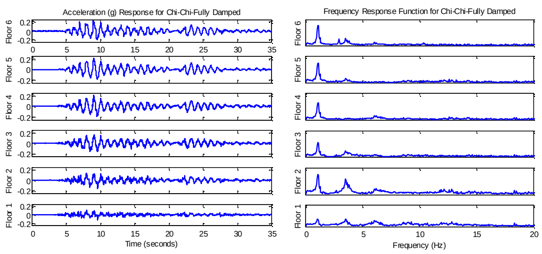
Chi-Chi Earthquake 1999

- **Role of wireless sensor during experimental testing:**
  - Record acceleration time history data
  - Calculates the complex-valued Fourier response function



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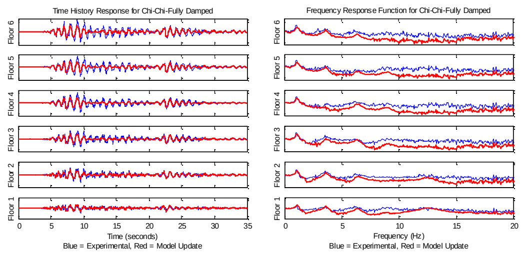
Simulated Annealing Results

- **Each sensor selects modal parameters (mass, stiffness, damping):**
  - Solve eigenvalue problem to yield model modal properties
  - Compare model modal properties to those experimentally derived



Rapid Assessment of Structural Condition and Stability Following a Terrorist Event
DHS Stabilization of Buildings Workshop, Vicksburg, Mississippi, August 25-27, 2009
University of Michigan

Monitoring Strategies for Rapid Assessment of Structural Condition and Stability Following a Terrorist Event

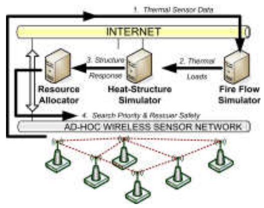
Andrew Zimmerman and Jerome Lynch

Model Updating Benefits

- **In the case of monitoring civil infrastructure to assess structural condition and stability following a terrorist event:**
  - CFD models can predict flow of heat – identify structural softening
  - Structural models can be used to predict damage and imminent collapse
  - Can even be used to predict behavior of people during evacuation
- **Computing within wireless sensor network advantageous:**
  - Local computing can save time and energy
  - Wireless sensors might not be able to invoke computational tools online
- **If connection with a cyberenvironment is possible:**
  - Can leverage powerful computational tools via the internet

Leveraging Cyberinfrastructure

- **Connecting dense sensor networks to simulation tools:**
  - Cyberinfrastructure tools now available to do this in an elegant way
  - Simulation tools run prediction models
  - Information passed back to the appropriate decision makers on site



Cyberinfrastructure for unifying sensor data with fire prediction simulators located on the internet

Summary and Conclusions

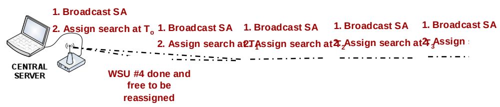
- **Terrorist loads on civil infrastructure likely to increase in the future:**
  - Requires more proactive approach to infrastructure protection
  - Monitoring technologies remain key
- **Critical need to explore new sensor types optimized for terrorism:**
  - Structural health monitoring
  - Tracking fire conditions and offering egress automation
  - Identifying and locating stranded inhabitants
- **Distributed sensing paradigm well suited for stability monitoring:**
  - Dense wireless sensor networks with distributed intelligence
  - Embedded data processing speeds data processing and decision making
  - Connection with cyberenvironment links data with models
  - Real-time structural stability assessment and fire prediction
- **Complete system for decision makers requires cyberenvironments!**

Thank-you!

Funding for some of the work presented herein has been provided by the National Science Foundation (NSF) and the Office of Naval Research (ONR).

Ad-hoc Implementation of WPSA

- **Approach the problem from an "agent" computing perspective:**
  - Parallelize the stochastic search over an entire wireless sensor network
    - Tremendous speed-up attainable on a very low computing platform
    - As "best" models are found, passed down to lower temperature steps
  - Once wireless sensor is done with search, free to be reassigned tasks
    - Autonomous and highly scalable to large sensor networks
    - Highly adaptable renders system resilient to failure



Monitoring Strategies for Rapid Assessment of Structural Condition and Stability Following a Terrorist Event

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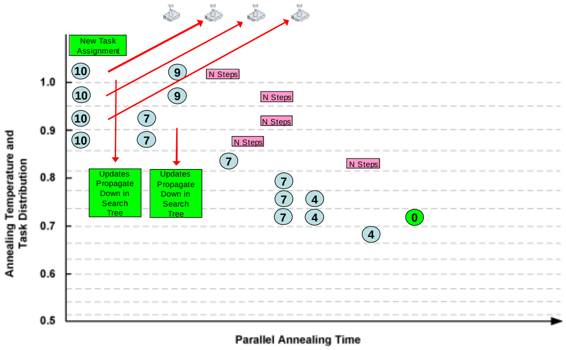
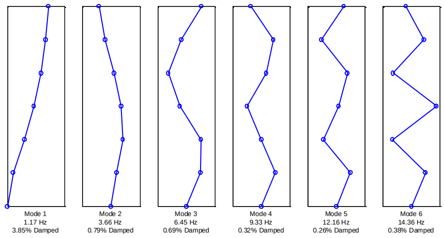
Parallelized Simulated Annealing



Identified Modal Properties

- Determine modal characteristics using embedded algorithms:
  - Peak picking to derive modal frequency
  - Frequency domain decomposition to yield mode shape
  - Random decrement to derive modal damping



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Assessment of Change in Structure

		Modal Parameters					
		Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
Damping Ratio	Dampers Disengaged	4.3%	1.3%	0.8%	0.6%	0.5%	0.4%
	Dampers Engaged - No Power	5.1%	7.8%	13.1%	18.1%	24.9%	25.4%
	Dampers Engaged - Full Power	5.0%	8.5%	14.8%	20.1%	27.5%	28.4%

		Structural Parameters					
		Floor 1	Floor 2	Floor 3	Floor 4	Floor 5	Floor 6
Mass (kg)	Dampers Disengaged	755	1293	1453	1236	1126	1965
	Dampers Engaged - No Power	752	1451	1443	1338	964	1937
	Dampers Engaged - Full Power	881	1791	1842	1853	1377	1970
Stiffness (kN/m)	Dampers Disengaged	0.56	1.69	3.44	1.68	2.49	1.36
	Dampers Engaged - No Power	0.55	2.77	1.63	1.61	1.97	2.64
	Dampers Engaged - Full Power	0.66	2.98	3.21	1.49	3.71	2.21

Increased Damping

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University of Michigan

Stabilization of Buildings Workshop
August 25–27, 2009
U.S. Army Corps of Engineers
Engineer Research and Development Center
Vicksburg, Mississippi

Structural Health Monitoring: Overview and Challenges Ahead

by

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Analytical Structural Dynamics Department
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Outline

- Sandia National Laboratories Interest in High Consequence Engineering
- Architectural Surety® Concepts
- Structural Health Monitoring Knowledge States
- Recent Development Trends
- Sandia Examples
- Future Challenges

Acknowledgements

- Mark Rumsey, Sandia, Wind Energy Technology
- Dennis Roach, Sandia, Infrastructure Surety
- Robert Nellums, Sandia, LDRI Sensors
- David Epp, Sandia, MEMS Sensors
- Todd Griffith, Sandia, Wind Turbine Blade Modeling & Testing
- Pavel Chaplya, Sandia, Material Modeling
- Rudy Matalucci, Sandia, Architectural Surety
- Robert Cranwell, Sandia, Condition Monitoring Prognostics
- Mahmoud Reda Taha, UNM, Damage Detection Algorithms

Mission-Driven Laboratory

We serve many agencies of the US Government with:

- Design and development: nonnuclear portions of US nuclear weapons
- Production: advanced components
- Safety, security, use control
- Treaty verification, nonproliferation, counterproliferation
- Advanced military technologies
- Energy and environment
- Homeland security, countering weapons of mass destruction

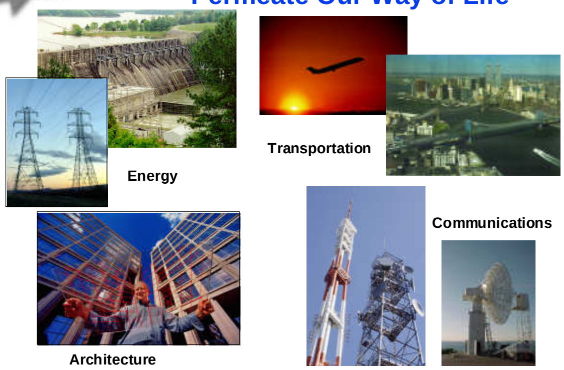
National Security Capability

Technology Transfer

Security of the Nuclear Stockpile
(B83 Strategic Bomb Components)

Security of a Federal Dam
(Critical Assets of Grand Coulee)

Critical Infrastructures Permeate Our Way of Life



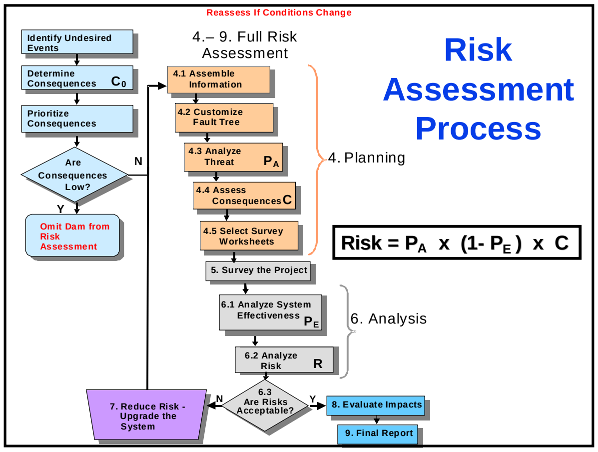
ASCE Report Card for America's Infrastructure

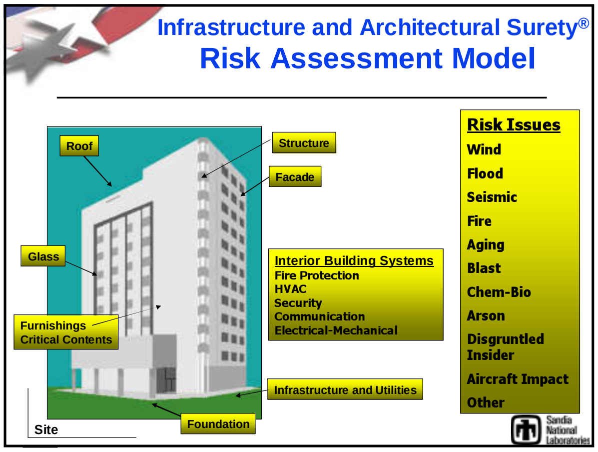
	1998	2001	2005
Roads	D-	D+	D
Bridges	C-	C	C
Transit	C	C-	D+
Aviation	C-	D	D+
Schools	F	D-	D
Drinking Water	D	D	D-
Wastewater	D+	D	D-
Dams	D	D	D
Solid Waste	C-	C+	C+
Hazardous Waste	D-	D+	D
Navigable Waterways	-	D+	D-
Energy	-	D+	D
Rail	-	-	C-
Public Parks & Recreation	-	-	C-
Security	-	-	I
GPA	D	D+	D

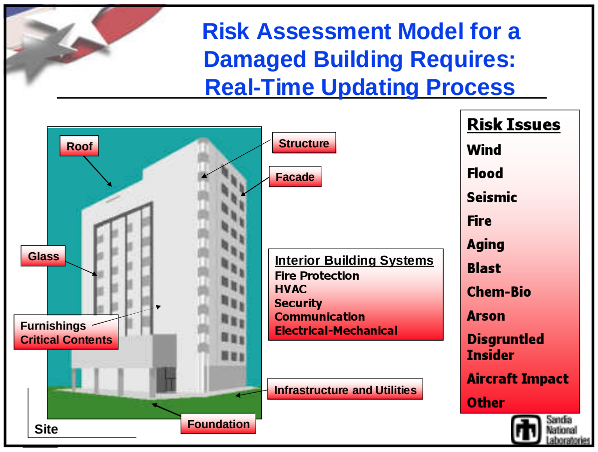
Infrastructure and Architectural Surety®

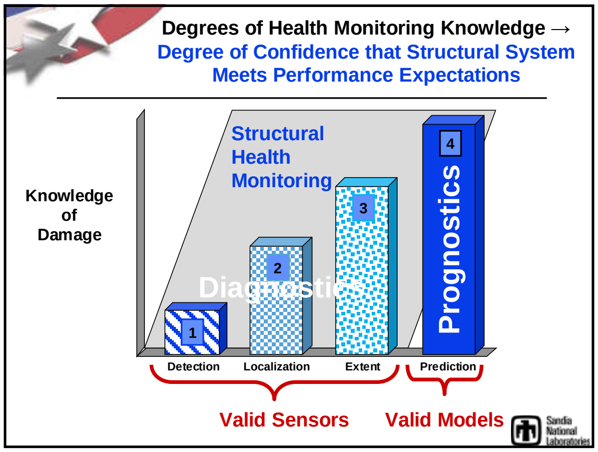
WHAT IS IT?

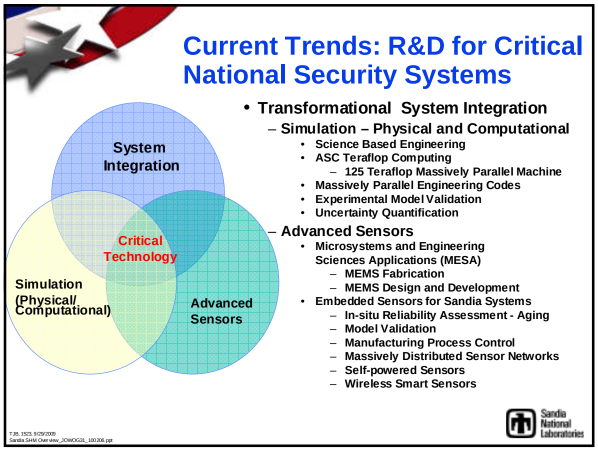
Architectural Surety®: a risk management approach to provide confidence that buildings and infrastructures will perform in acceptable ways under various threat environments

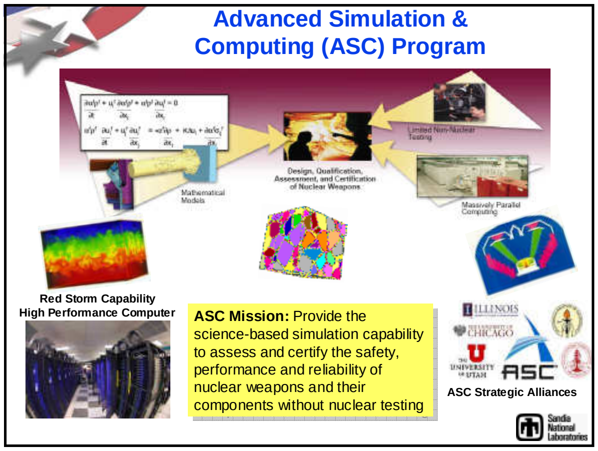


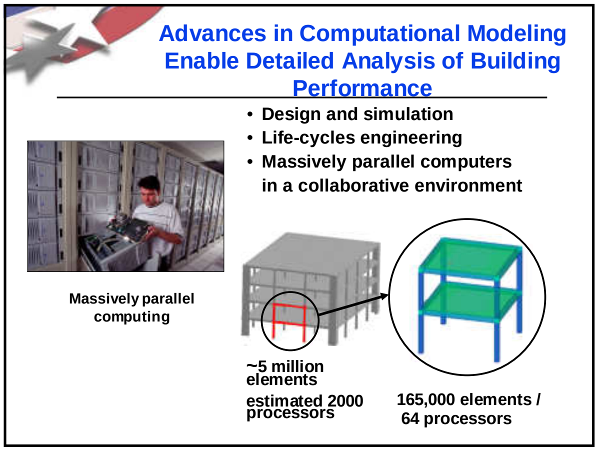


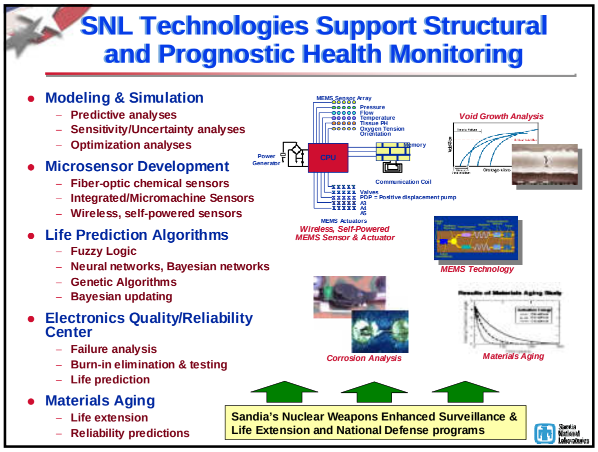


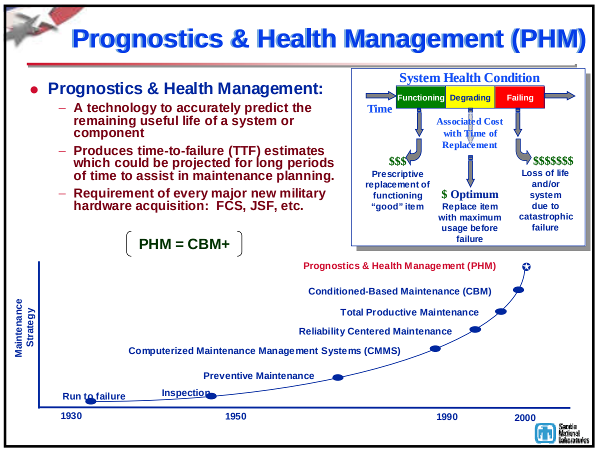


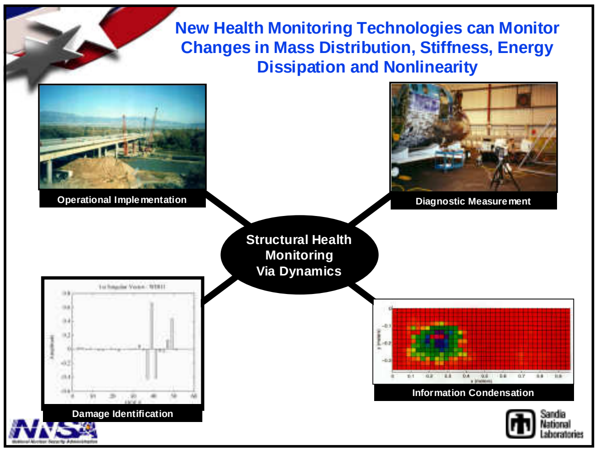

Current Trends: R&D for Critical National Security Systems
System Integration
Critical Technology
Simulation (Physical/ Computational)
Advanced Sensors
• Transformational System Integration
– Simulation – Physical and Computational
• Science Based Engineering
• ASC Teraflop Computing
– 125 Teraflop Massively Parallel Machine
• Massively Parallel Engineering Codes
• Experimental Model Validation
• Uncertainty Quantification
– Advanced Sensors
• Microsystems and Engineering Sciences Applications (MESA)
– MEMS Fabrication
– MEMS Design and Development
• Embedded Sensors for Sandia Systems
– In-situ Reliability Assessment - Aging
– Model Validation
– Manufacturing Process Control
– Massively Distributed Sensor Networks
– Self-powered Sensors
– Wireless Smart Sensors
Sandia National Laboratories


Advanced Simulation & Computing (ASC) Program
Mathematical Models
Design, Qualification, Assessment, and Certification of Nuclear Weapons
Limited Non-Nuclear Testing
Massively Parallel Computing
Red Storm Capability
High Performance Computer
ASC Mission: Provide the science-based simulation capability to assess and certify the safety, performance and reliability of nuclear weapons and their components without nuclear testing
ILLINOIS
CHICAGO
UNIVERSITY OF UTAH
ASC
ASC Strategic Alliances
Sandia National Laboratories


Advances in Computational Modeling Enable Detailed Analysis of Building Performance
• Design and simulation
• Life-cycles engineering
• Massively parallel computers in a collaborative environment
Massively parallel computing
~5 million elements
estimated 2000 processors
165,000 elements / 64 processors

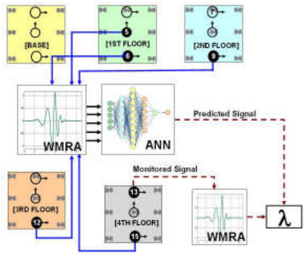

SNL Technologies Support Structural and Prognostic Health Monitoring
• Modeling & Simulation
– Predictive analyses
– Sensitivity/Uncertainty analyses
– Optimization analyses
• Microsensor Development
– Fiber-optic chemical sensors
– Integrated/Micromachine Sensors
– Wireless, self-powered sensors
• Life Prediction Algorithms
– Fuzzy Logic
– Neural networks, Bayesian networks
– Genetic Algorithms
– Bayesian updating
• Electronics Quality/Reliability Center
– Failure analysis
– Burn-in elimination & testing
– Life prediction
• Materials Aging
– Life extension
– Reliability predictions
Wireless, Self-Powered MEMS Sensor & Actuator
Void Growth Analysis
MEMS Technology
Corrosion Analysis
Materials Aging
Sandia's Nuclear Weapons Enhanced Surveillance & Life Extension and National Defense programs


Prognostics & Health Management (PHM)
• Prognostics & Health Management:
– A technology to accurately predict the remaining useful life of a system or component
– Produces time-to-failure (TTF) estimates which could be projected for long periods of time to assist in maintenance planning.
– Requirement of every major new military hardware acquisition: FCS, JSF, etc.
PHM = CBM+
System Health Condition
Time
Functioning
Degrading
Failing
Associated Cost with Time of Replacement
$$$
Prescriptive replacement of functioning "good" item
$ Optimum
Replace item with maximum usage before failure
$$$$$$$
Loss of life and/or system due to catastrophic failure
Maintenance Strategy
Prognostics & Health Management (PHM)
Conditioned-Based Maintenance (CBM)
Total Productive Maintenance
Reliability Centered Maintenance
Computerized Maintenance Management Systems (CMMS)
Preventive Maintenance
Run to failure
Inspection
1930
1950
1990
2000


New Health Monitoring Technologies can Monitor Changes in Mass Distribution, Stiffness, Energy Dissipation and Nonlinearity
Operational Implementation
Diagnostic Measurement
Structural Health Monitoring Via Dynamics
Damage Identification
Information Condensation
NNSA
Sandia National Laboratories

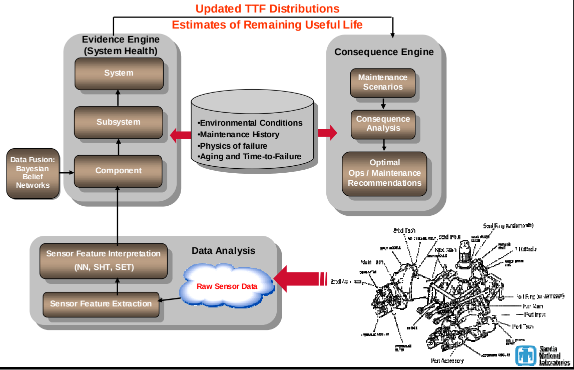
Damage Detection Algorithms – Convert Data into Insight

Experimental Validation



McCuskey, M., Reda Taha, M.M., Horton*, S., and Baca, T. J. "Identifying Damage in ASCE Benchmark Structure using a Neural-Wavelet Module", Proceedings of the International Workshop on Structural Health Monitoring, Granada, Spain, July 2006.*

Sandia PHM System Architecture



Recent SHM Technology Development Trends *

- Data analysis for improved signal-to-noise measurements and optimized flaw detection
- Lamb waves and wave propagation (wavelet analysis algorithms)
- Data compression and filtering to accommodate continuous monitoring
- Acoustic emissions
- Piezoelectric sensors and spatial resolution
- Capacitive, electromagnetic, and eddy current sensors
- Fatigue sensors
- Fiber optic and Fiber Bragg Grating systems
- Load (strain gage) and vibration (accelerometer) monitoring methods
- Wireless sensors and energy harvesting
- Data fusion for enhanced SHM using multiple sensor systems
- Modeling and simulation to guide SHM design
- Capacitive micro ultrasonic transducers (cMUT)
- Multi-mode and frequency differential Lamb wave imaging to optimize flaw detection (interpret signals) and minimize the number of sensors needed for in-situ SHM applications
- Neural networks and automated pattern recognition for autonomous "smart" SHM systems
- Extrapolation of SHM into Prognostics Health Management and Condition Based Maintenance practices

*European Conference on Structural Health Monitoring - July, 2008

Example: Wind Turbine Structural Health Monitoring

Sensing Opportunities

Current location of sensors on a utility size wind turbine
- Nacelle – lots
- Tower Base – lots
- Blades – **few to no sensors!**

Desire for real-time blade sensing
- Maximize structural and aero efficiency
- Advanced controls strategies
- Damage detection and Structural health monitoring
- Increase reliability and energy capture

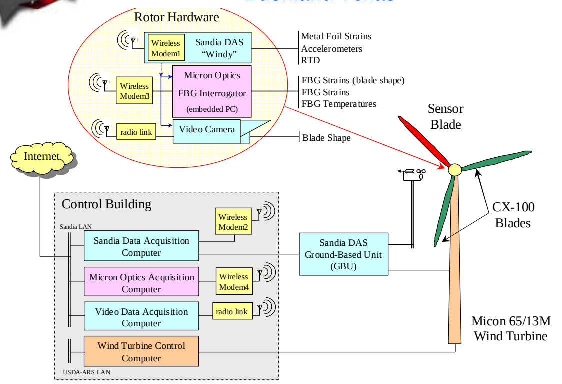
Goal is a Smart Wind Turbine Structure

Sensor Blade (SBlade) Project

- **Build a Sensor Blade** (TPI Composites, Inc., Warren, Rhode Island)
  - Incorporate sensors in a blade during blade manufacture
  - Sensor list:
    - Embedded FBG sensors (strain and temperature, blade shape)
    - Inner-surface mounted FBG sensors (strain and temperature, loads)
    - Inner-surface mounted accelerometers (blade shape, loads, SHM)
    - Metal foil strain gages (strain, loads)
    - RTD temperature
    - Streaming video on rotor (blade shape)
- **Field Test Sensor Blade** (U.S. Department of Agriculture – Agriculture Research Service, Bushland, Texas)
  - On-the-ground checkouts and calibrations
  - In-the-air checkouts and calibrations
  - Measure loads and blade deflections during turbine operation
  - Real-time video monitoring
- **Static and Fatigue Test Sensor Blade** (National Renewable Energy Laboratory / National Wind Technology Center, Boulder, Colorado)
  - AE NDT and SHM
  - Static Proof Test
  - Fatigue test to SBlade failure
- **Analyze datasets and report results**

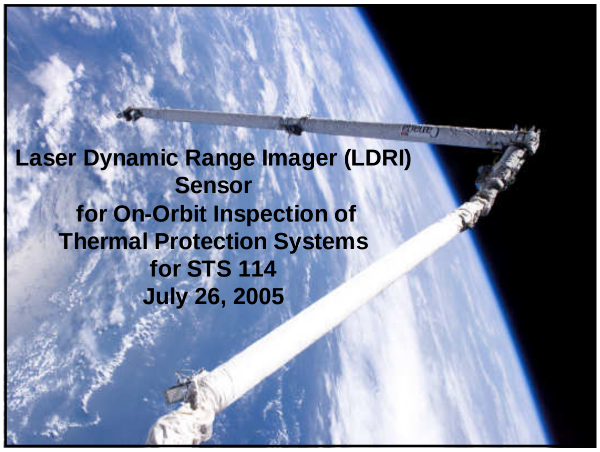
TX-100 fabrication at TPI Composites

Field Test SBlade at USDA-ARS, Bushland Texas



Example: On-Orbit Space Shuttle Structural Health Monitoring

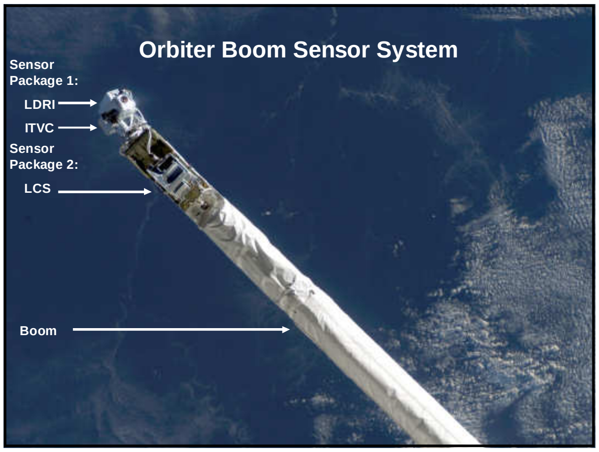
Iberdrola Visit



SHM Sensor System Development Background

- LDRI Development History:
  - The Laser Dynamic Range Imager (LDRI) was developed at Sandia from 1997-2000, to support modal testing of the International Space Station on STS-97, which concluded successfully.
- LDRI Orbital Inspection System (LOIS) Project Origin
  - Following the Columbia disaster, the Shuttle program issued a requirement for on-orbit 3-D inspection of the Thermal Protection System.
  - Sandia LDRI and the Canadian LCS systems were identified as the only systems capable of being developed and meeting schedule.
- LOIS Schedule
  - The LOIS project received a go-ahead 10/03
  - PDR was 4/04, CDR was 6/04, Engineering Development Unit demonstration was 8/04, Flight Unit delivery was 12/04.
  - NASA testing and flight certification was completed in time for the May 05 launch date, which was subsequently delayed to July 26.

Sandia National Laboratories



On-Orbit Inspection Milestones

- Day 2: Scan RCC surfaces using OBSS
  - All Leading-edge surfaces of the Nose and Wing
  - Detect all damage, down to 0.030" cracks or exposed substrate
- Day 2: Scan Tile surfaces using ISS cameras
  - Detect damage, down to 1"
- Day 5+: Focused Inspection using OBSS
  - Previously Detected Areas of Interest

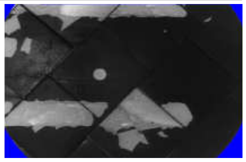
Sandia National Laboratories

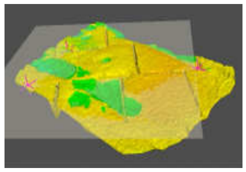
Sandia System Components

- 4 LDRI Flight Sensors
  - Integrated into Shuttle Closed Circuit TV System
  - Completed CRIT1R flight certification

LDRI Workstation Operation

- Continuous DV Intake
- Continuous Video Output
  - Intensity Images Only
  - Level 1 Enhancements
- Post Processing Output
  - Higher level intensity enhancements
  - 3-D Processing





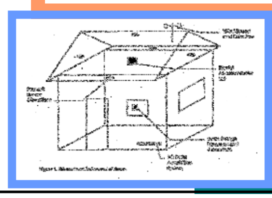
NASA Committed to SHM for Manned Spacecraft

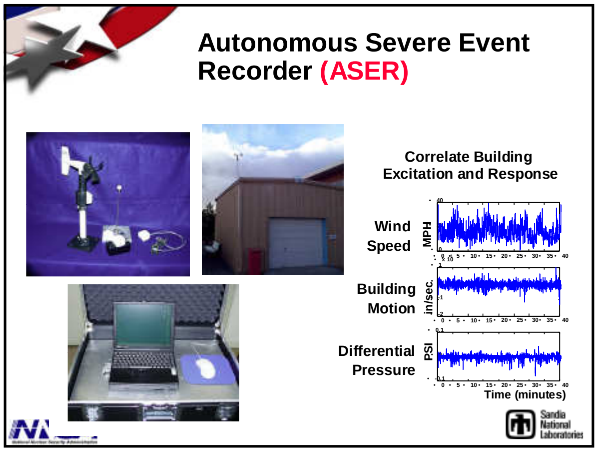
NASA Initiative for Integrated Systems Health Monitoring (ISHM)

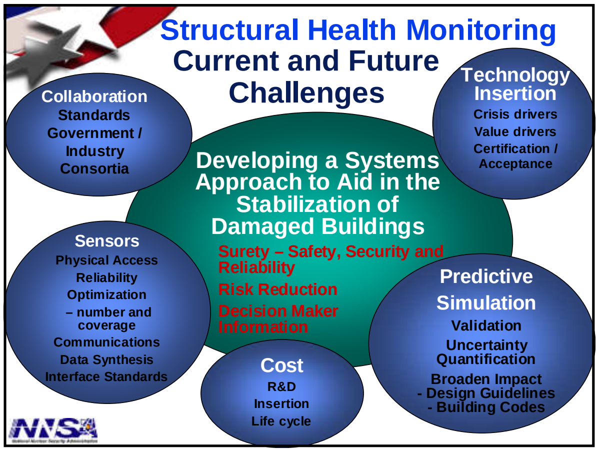
- Crew Exploration Vehicle (CEV)
  - Thermal Protection System Technology Development
  - Integrated Systems Health Monitoring (ISHM) Oversight/Requirements Development
- Crew Launch Vehicle (CLV)
  - Expertise in Integrated Systems Health Monitoring (ISHM)
    - Design and development phase health monitoring requirements analysis
    - CLV element fault detection algorithms development
    - DDT&E and V&V tools development
  - Support reliability assessment with Monte Carlo simulations
  - Ascent Abort CFD Blast Analysis

Example: Autonomous Severe Event Recorder

Model and Measure Loads and Responses
Severe Winds




Autonomous Severe Event Recorder (ASER)
Correlate Building Excitation and Response
Wind Speed
MPH
Building Motion
in/sec.
Differential Pressure
PSI
Time (minutes)
Sandia National Laboratories


Structural Health Monitoring
Current and Future Challenges
Collaboration
Standards
Government / Industry Consortia
Technology Insertion
Crisis drivers
Value drivers
Certification / Acceptance
Developing a Systems Approach to Aid in the Stabilization of Damaged Buildings
Surety – Safety, Security and Reliability
Risk Reduction
Decision Maker Information
Sensors
Physical Access
Reliability
Optimization
– number and coverage
Communications
Data Synthesis
Interface Standards
Cost
R&D
Insertion
Life cycle
Predictive Simulation
Validation
Uncertainty Quantification
Broaden Impact
- Design Guidelines
- Building Codes
NNSA


Questions?
NNSA
Sandia National Laboratories

Structural Integrity Monitoring System for Detecting Imminent Collapse of Buildings

Feng-Bao Lin, Tony Wu and Anil Agrawal

Department of Homeland Security
August 25-27, 2009 Vicksburg, MS

STRUCTURAL INTEGRITY MONITORING SYSTEM FOR DETECTING IMMINENT COLLAPSE OF BUILDINGS

Feng-Bao Lin, Tony Wu and Anil Agrawal

Department of Civil Engineering
The City College of New York
New York, NY 10031

Life Safety During Building Fire

- Building fires pose significant risk to occupants and first responders.
- First responders face significant risks because of uncertainties involving collapse of structural components.
- Although there are field guidelines based on past experiences, very few technological solutions to predict imminent collapse of a building.
- With progress in sensing and computing technology, a multi-sensing tool capable of warning firefighters can be developed.

The City College of New York

DYNAMICS AND STRUCTURAL CONTROL LABORATORY

Motivation and Needs

- During a fire caused by an explosive attack, material strength and stiffness deteriorates with temperature.
- It is expected that change in structural stiffness prior to collapse would be rapid enough to cause a dynamic-like action leading to structural vibrations.
- For example, some firefighters have reported that they experienced a noticeable level of vibration before the onset of collapse.

The City College of New York

DYNAMICS AND STRUCTURAL CONTROL LABORATORY

Motivation and Needs

- This implies that an incipient collapse of a structure due to fire damage may be detected by monitoring the dynamic characteristics of the structural system using a vibration modal analysis method.
- Such observations and experiences can be utilized to develop a multi-sensory system to develop structural integrity system to monitor imminent collapse.
- A data fusion approach can be used to combine data from different sensors for reliable decision making.

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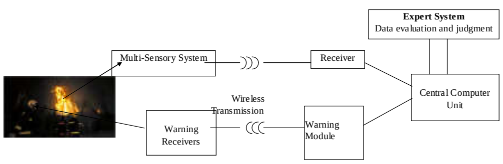
DYNAMICS AND STRUCTURAL CONTROL LABORATORY

Multi-Sensory Structural Integrity System

An early warning system for firefighters that detects structural damage caused by fire and other hazards to predict imminent collapse.



The City College of New York

DYNAMICS AND STRUCTURAL CONTROL LABORATORY

Sensory Requirements

- Multi-sensory system for decision making on the basis of all possible information: Temperature, vibrations, laser, infrared camera, ultrasonic, acoustic emissions, etc.
- Mobile field deployment capability for fast deployment at the fire scene.
- Sensors must be able to withstand extremely harsh environments, such as elevated temperatures, toxic gases, various noises, and low visibility.

The City College of New York

DYNAMICS AND STRUCTURAL CONTROL LABORATORY

Sensory Requirements

– Wireless transmission of data between building components and central processing unit.

– Decision based on on-site measurements only. Instant analysis and decision making using an expert system built on the basis of past experience of firefighters and sound technical knowledge.

The City College of New York

DYNAMICS AND STRUCTURAL CONTROL LABORATORY

Decision Making

Detect if damage has occurred
Determine the location of damage
Estimate damage severity

↓ Expert System: Correlation between sensory outputs and experiences and scenarios

Evaluate the consequences on the structure and issue appropriate instructions

The City College of New York

DYNAMICS AND STRUCTURAL CONTROL LABORATORY

Dynamic Monitoring of Beams: An Illustration

Test of 40-in Wood (1" × 1-7/16") and Aluminum (1"x2") Beams:

- Load both beams to $0.5P_u$ by a concentrated load at mid-span.
- Increase the temperature at the mid-span using heat-lamps at the rate of 10°F/min till both beams fail.
- Apply small impact at both beams to measure acceleration impulse at every 50°F increase in temperature.
- Analyze impulse data to identify change in the behavior of the beam.

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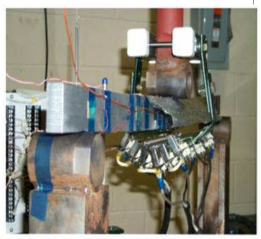
DYNAMICS AND STRUCTURAL CONTROL LABORATORY

Dynamic Monitoring of Beams: An Illustration

Wood Beam

Aluminum Beam



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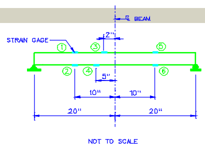
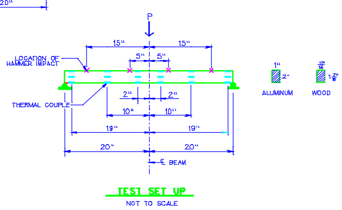
Dynamic Monitoring of Beams: An Illustration



Strain Gauge Locations



Thermocouple and Accelerometer Locations

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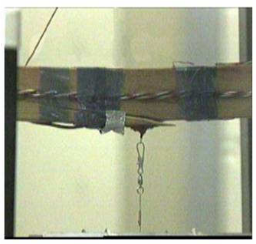
Dynamic Monitoring of Beams: An Illustration



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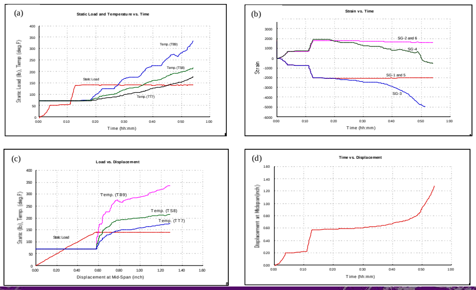
Structural Integrity Monitoring System for Detecting Imminent Collapse of Buildings

Feng-Bao Lin, Tony Wu and Anil Agrawal

DYNAMICS AND STRUCTURAL CONTROL LABORATORY

Dynamic Monitoring of Beams: An Illustration

Wood Beam



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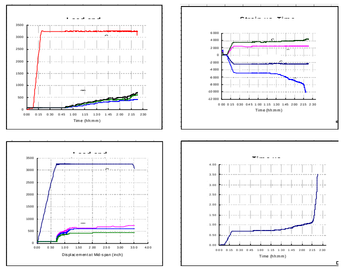
Dynamic Monitoring of Beams: An Illustration

Aluminum Beam



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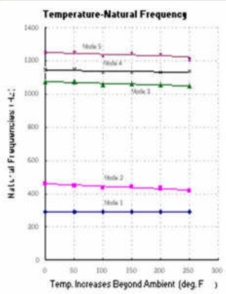
Dynamic Monitoring of Beams: An Illustration



No significant change in natural frequency of the wood beam observed.

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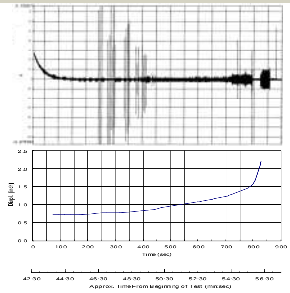
Dynamic Monitoring of Beams: An Illustration



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Dynamic Monitoring of Beams: An Illustration

- The goal of the study was to show the potential of the multi-sensory approach through a very simple approach.
- Very detailed study, including selection of various sensors integrated into one platform, are is planned.
- A decision making tool using data-fusion approach can give reliable prediction of imminent collapse:
- Vibration signal (accelerometers) + Acoustic Emission + Temperature + knowledgebase on behavior (displacement, connections behavior, etc.) of beams during fire = More reliable estimation of imminent collapse

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Example of Multi-Sensory Systems for Underground Pipes

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Rescue of Victims during a Catastrophic Event

Mobile phones can be used as multi-sensory devices.

A simple RFID type sensor embedded in cell phone can send signal from victim to the rescue team.

Victim can be located by triangulation of signals from several cell phones on site.

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Rescue of Victims during a Catastrophic Event

Sensors transmitting victim's condition (heart beat) can be integrated.

Technology deployable with minimal costs by telecommunication companies.

Significant impact on rescue operations.

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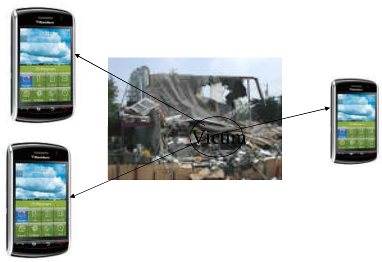
Rescue of Victims during a Catastrophic Event



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DYNAMICS AND STRUCTURAL CONTROL LABORATORY

Conclusions

Multi-sensory approach has potential to detect imminent collapse of building members.

However, the observation is based on very limited data. Extensive work is needed on:

- Effective sensory components capable of withstanding harsh environment
- Data fusion based expert system for instant decision making.

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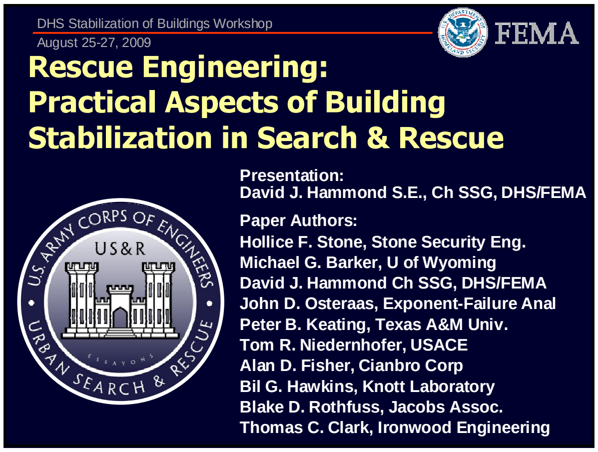
DHS Stabilization of Buildings Workshop
August 25-27, 2009
FEMA
Rescue Engineering: Practical Aspects of Building Stabilization in Search & Rescue
Presentation:
David J. Hammond S.E., Ch SSG, DHS/FEMA
Paper Authors:
Hollice F. Stone, Stone Security Eng.
Michael G. Barker, U of Wyoming
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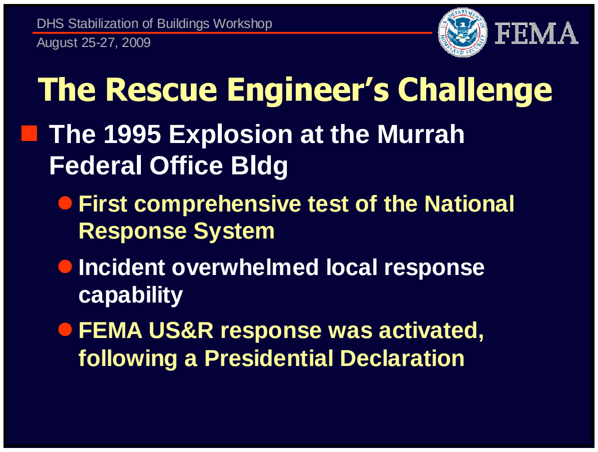
John D. Osteraas, Exponent-Failure Anal
Peter B. Keating, Texas A&M Univ.
Tom R. Niedernhofer, USACE
Alan D. Fisher, Cianbro Corp
Bil G. Hawkins, Knott Laboratory
Blake D. Rothfuss, Jacobs Assoc.
Thomas C. Clark, Ironwood Engineering
U.S. ARMY CORPS OF ENGINEERS
US&R
URBAN SEARCH & RESCUE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The Rescue Engineer's Challenge
The 1995 Explosion at the Murrah Federal Office Bldg
First comprehensive test of the National Response System
Incident overwhelmed local response capability
FEMA US&R response was activated, following a Presidential Declaration


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N. Side of 10 Story, Murrah Bldg (Concrete)
20'x35' Column spacing with Transfer Beam at 3rd Fl


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S. Side of 10 story, Murrah Bldg
Showing shearwalls at stairs & elevator
Pre-cast panel facade - Plaza at 2nd Fl w/ Main Entry


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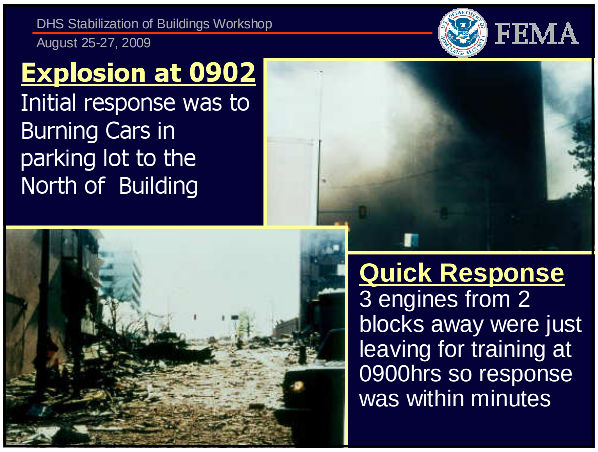
FEMA
Simulated Collapse
HE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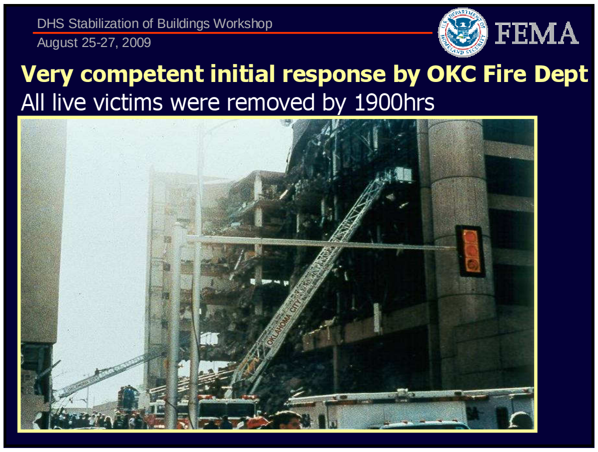
Explosion at 0902
Initial response was to Burning Cars in parking lot to the North of Building
Quick Response
3 engines from 2 blocks away were just leaving for training at 0900hrs so response was within minutes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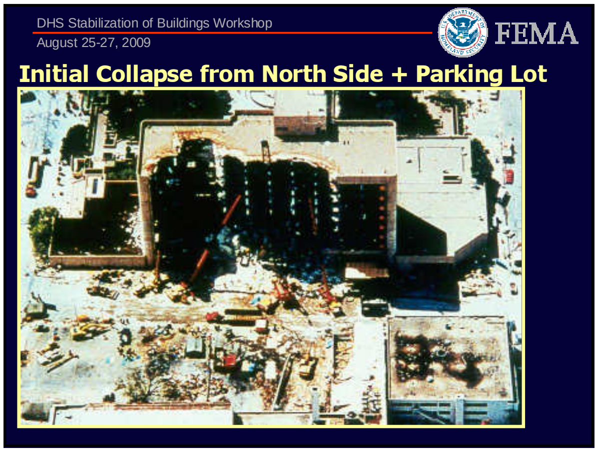
Very competent initial response by OKC Fire Dept
All live victims were removed by 1900hrs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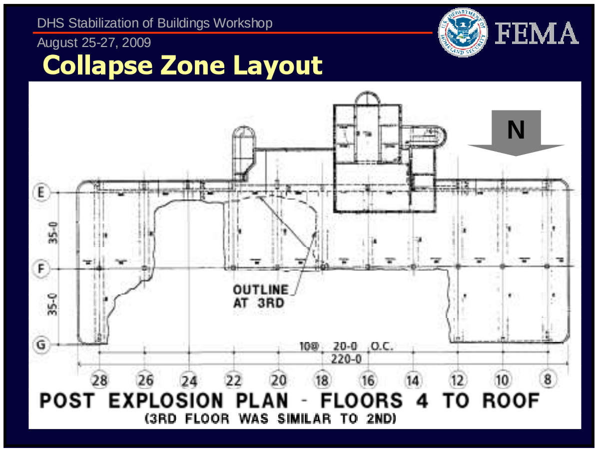
Initial Collapse from North Side + Parking Lot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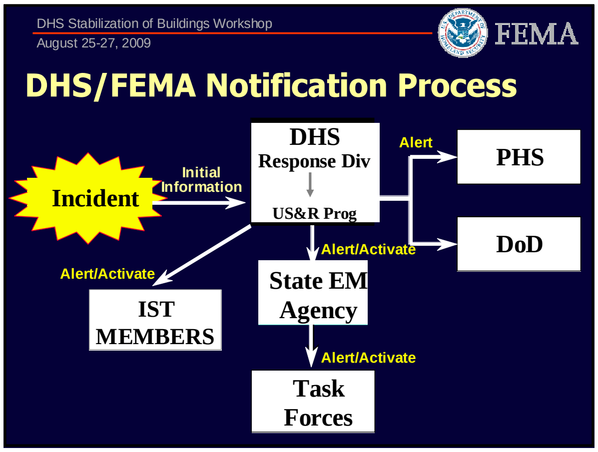
FEMA
Collapse Zone Layout
N
E
F
G
35-0
35-0
OUTLINE AT 3RD
10@ 20-0 O.C.
220-0
28
26
24
22
20
18
16
14
12
10
8
POST EXPLOSION PLAN - FLOORS 4 TO ROOF
(3RD FLOOR WAS SIMILAR TO 2ND)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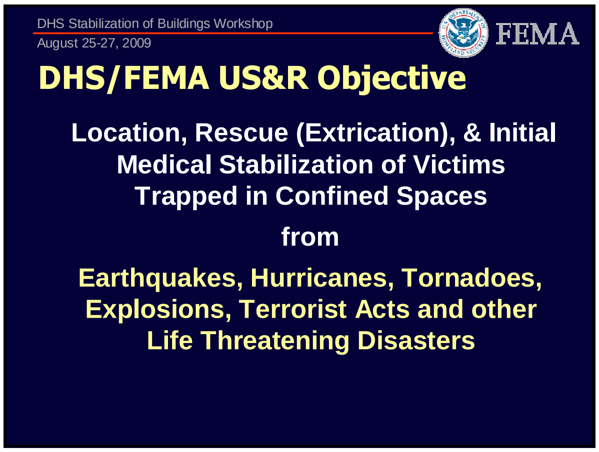
FEMA
DHS/FEMA Notification Process
Incident
Initial Information
DHS
Response Div
US&R Prog
Alert
PHS
DoD
Alert/Activate
State EM Agency
Alert/Activate
IST MEMBERS
Alert/Activate
Task Forces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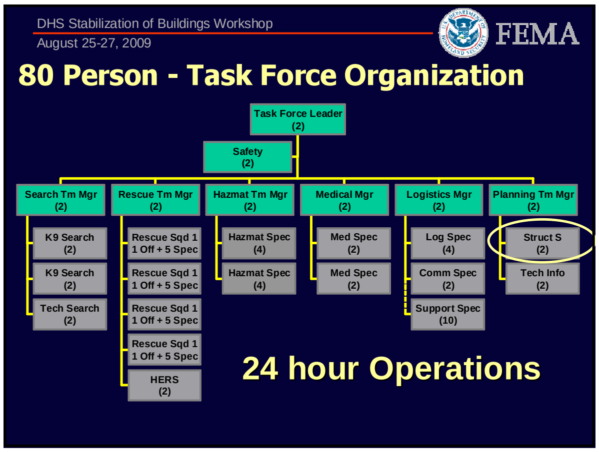
DHS/FEMA US&R Objective
Location, Rescue (Extrication), & Initial Medical Stabilization of Victims Trapped in Confined Spaces
from
Earthquakes, Hurricanes, Tornadoes, Explosions, Terrorist Acts and other Life Threatening Disasters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80 Person - Task Force Organization
Task Force Leader (2)
Safety (2)
Search Tm Mgr (2)
Rescue Tm Mgr (2)
Hazmat Tm Mgr (2)
Medical Mgr (2)
Logistics Mgr (2)
Planning Tm Mgr (2)
K9 Search (2)
K9 Search (2)
Tech Search (2)
Rescue Sqd 1 1 Off + 5 Spec
Rescue Sqd 1 1 Off + 5 Spec
Rescue Sqd 1 1 Off + 5 Spec
Rescue Sqd 1 1 Off + 5 Spec
HERS (2)
Hazmat Spec (4)
Hazmat Spec (4)
Med Spec (2)
Med Spec (2)
Log Spec (4)
Comm Spec (2)
Support Spec (10)
Struct S (2)
Tech Info (2)
24 hour Operations

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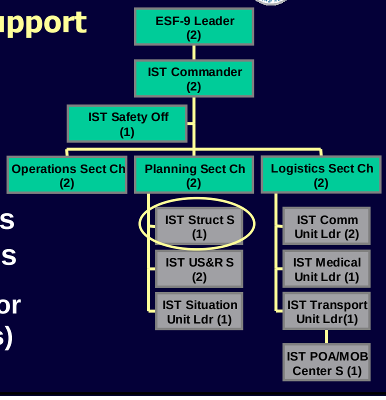
Incident Support Team - A



20 Positions
24 Hour Ops

(may add 6 for full 24 hr ops)

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The US&R Structures Specialist's (StS) Role

- Provide:
  - Hazard I.D. & Assessment
  - Hazard Mitigation Alternatives
  - Monitoring Techniques
- Engineers need to give their best possible assessment & advice
  - Persuasively but within Incident Command Sys
- Rescue focus is on victims - Engineer focus is safety of Rescue Forces

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StS Basic Approach

Identify & Solve

- What caused collapse?
- What type (types) of structure?
  - Condition of Vertical Load Path
  - Condition of Lateral Load Path
- What type hazards present
  - Collapse, Falling, Other
- Location & condition of voids
- Locations of original Access/Holes
- Needed Access for Search & Rescue
- Available Mitigation Methods

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FEMA US&R TFs arrive by 2000hrs

IST was fully staffed over next 24hrs

IST Struct Spec started by doing Hazard Assessment starting on North side at East end

Note that East end is poorly connected to remainder of building

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North East Corner Looking West

Note that "The Bite" has been created by the collapse of Column F-24

Also note that the 2nd & 3rd floors are missing on all sides of Columns F-22 & F-20

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Moving West on North side to Lines 18 thru 24

Columns F-22 & F-20 are unbraced for 3 stories and have about 300k & 500k loading

The debris appear to be providing some column bracing but it needs to be removed - at daycare center


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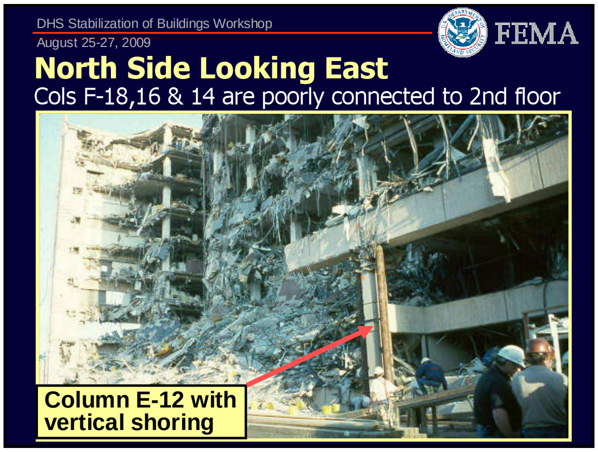
FEMA
North Side
at West End
Column E-12 has Vertical Shoring installed during Day 1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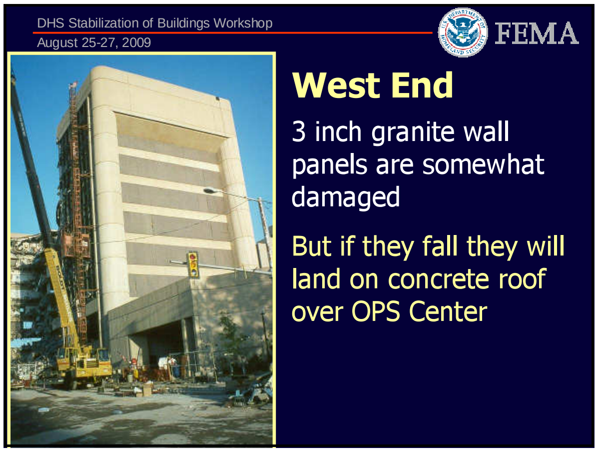
North Side Looking East
Cols F-18,16 & 14 are poorly connected to 2nd floor
Column E-12 with vertical shoring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West End
3 inch granite wall panels are somewhat damaged
But if they fall they will land on concrete roof over OPS Center


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August 25-27, 2009
FEMA
South Side
Main Entry at 2nd fl -
See next slide


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August 25-27, 2009
FEMA
Precast Panels over Main Entry
Cable tied on 1st day by local contractor, O.K.


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FEMA
East End
Granite panels have partly fallen, but land on concrete roof below - can create fall zone

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FEMA

Return to North Side

Note large number of hanging slabs
Plus Large (35k) Mother Slab

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Need to sit down for a few minutes & Review

- COLLAPSE HAZARDS
  - E Tower Marginally stable
  - Columns F-20 & F-22 have 2nd & 3rd floor ripped away and 4" dia pipe installed - INADEQUATE
  - Columns F-16 & F-18 poorly connected to 2nd floor
  - Column E-12 - Vertical Shore installed- O.K.
- FALLING HAZARDS
  - South Entry P.C. Spandrel - Cable tied O.K.
  - East & West Granite wall veneer - Fall zone is concrete roof - O.K.
  - Hanging Slabs on North Face
  - Mother Slab

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Column E-12

Adequately shored on Day 2, 20Apr95 by local contractor Boldt Construction

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East Tower

Marginally stable

Monitor from north parking lot using Theodolite + establish link to weather service to warn of winds over 25MPH

Can't establish fall zone - would greatly limit rescue efforts

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Theodolite in North Parking Lot for East Tower

One also located East of bldg to check Wall Line E

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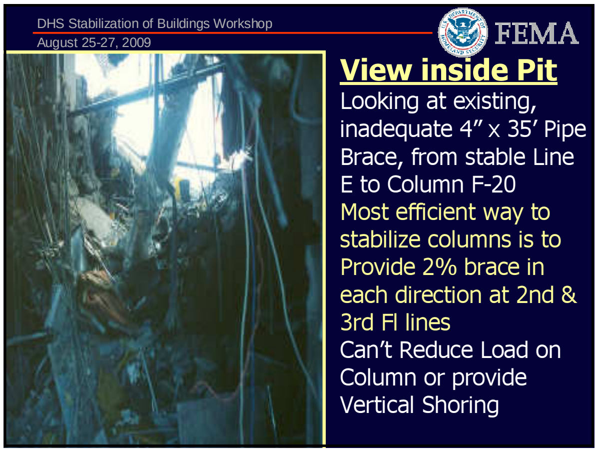
While the TFs were Shoring 2nd Floor

The Top Priority for IST StS was to work w/Contractors to Brace Columns F-22 & F-20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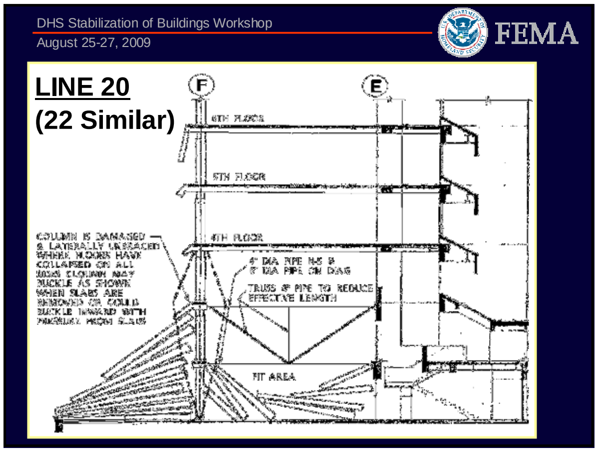
FEMA
View inside Pit
Looking at existing, inadequate 4" x 35' Pipe Brace, from stable Line E to Column F-20
Most efficient way to stabilize columns is to Provide 2% brace in each direction at 2nd & 3rd Fl lines
Can't Reduce Load on Column or provide Vertical Shoring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LINE 20
(22 Similar)
F
E
6TH FLOOR
5TH FLOOR
4TH FLOOR
PIT AREA


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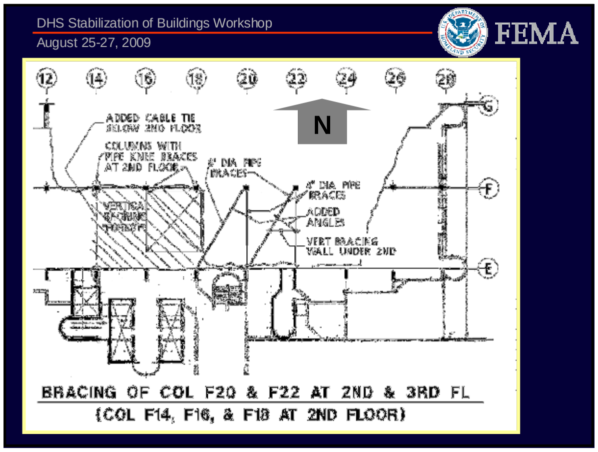
Many people + Crane pull to lift in bigger pipes
Needed to work in concert w/ rescue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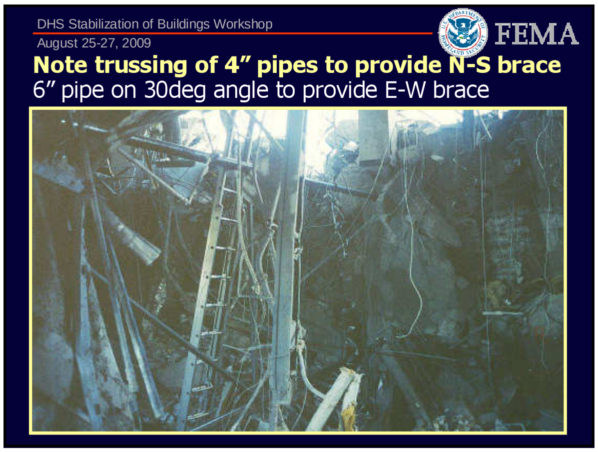
FEMA
N
BRACING OF COL F20 & F22 AT 2ND & 3RD FL
(COL F14, F16, & F18 AT 2ND FLOOR)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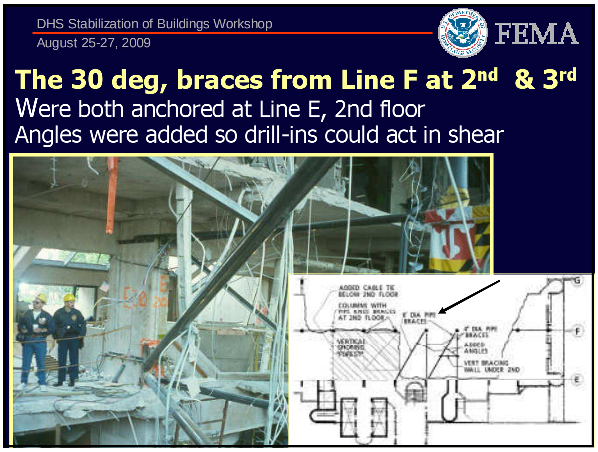
Note trussing of 4" pipes to provide N-S brace
6" pipe on 30deg angle to provide E-W brace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The 30 deg, braces from Line F at 2nd & 3rd
Were both anchored at Line E, 2nd floor
Angles were added so drill-ins could act in shear

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End of Week 1

Pipe braces & Cable ties for F20, F22

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Column F-22

As debris slabs were removed the cracked nature of the concrete where the floor slabs had been ripped away was revealed

Metal packaging tape was placed around the column at the damaged area

The Quickest Fix

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It was then decided to carefully remove the projecting rebar in order to apply a grout filled, steel sleeve

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Cols F-20 & 22

Steel sleeves from 3/8" plate & angles were placed at 3rd fl.
Then filled w/fast set grout

Also pipe braces were tied into the sleeves & new collars to more positively attach to column

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Cols F-18, 20 & 22

Smart Levels were then placed to monitor column rotation (buckling mode)
between 2nd & 3rd floors

Used binoculars from the safer area near Line E

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Cols F-20 & 22 with final Sleeves & Bracing

Work continued from Day 3 to 12

As the **Reward** chances got Less, the **Risk** needed to become Less

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Wood shores supporting 2nd floor
The Forest

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Column F-14

Showing how beam has dropped 3ft.

Wood Shoring supports Vertical Load & Cable

Tieback holds it from moving North when debris are removed to access Victim

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Hanging Slabs on North face of collapse

Were originally NOT considered as a high priority Falling Hazard

By Day 6 rescuers became concerned as the wind continued to cause small pieces of concrete to fall, thereby slowing Rescue Operations

Each individual slab was evaluated by FEMA StS then OCFD agreed to allow slabs to be removed

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Some slabs were removed by cutting & dropping into a dumpster held by crane

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Finally North Face of structure was cleaned of Falling Hazards and Fenced

Note that the remaining floor slabs had their bottom rebar pulled out adjacent to the initial collapse - This area was unsafe and avoided

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Summary - Murrah Bldg Experience

- A total of 11 TFs and an equal number of OCFD personnel toiled for a total of 15 days to recover the 168 victims.
  - A total of 37 StS were deployed
- The FEMA US&R Response System operated well (without serious accident) and passed it's first big test as a competent disaster responder.
- Lessons were learned regarding use of equipment, personnel, & communication.

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The Collapsed Structure Disaster Work Environment

Presentation:
Hollice Stone, P.E.
Stone Security Engineering
USACE StS, formerly CA-TF3

Paper Authors:
David J. Hammond S.E.
Michael G. Barker, U of Wyoming
Tom R. Niedernhofer, USACE

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Introduction to US&R System

U.S. Department of Homeland Security Mission

- Prevent terrorist attacks within the United States
- Reduce America's vulnerability to terrorism
- Minimize the damage from potential attacks and natural disasters

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U.S. Dept of Homeland Security Organization

- Combined 22 Federal agencies into four policy directorates:
  - Border and Transportation Security
  - Emergency Preparedness and Response
  - Information Analysis and Infrastructure Protection
  - Science and Technology
- Management Directorate
- U.S. Coast Guard
- U.S. Secret Service

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DHS/FEMA as an Organization

- Part of Dept of Homeland Security
- D.C. Hq + 10 Regional offices
- About 2000 full time employees
- About 10,000 DAEs
- Presidential appointment for:
  - Emergency Prep, & Response Div Director
  - Regional Directors
  - Field Coordinating Officers - FCO

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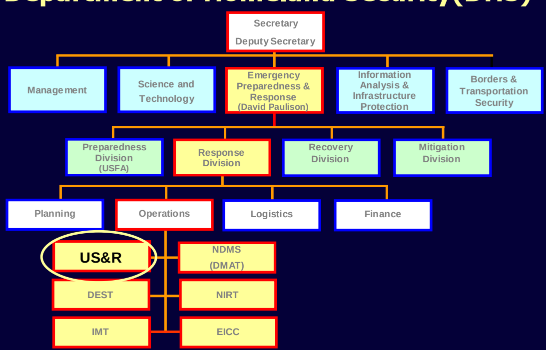
Department of Homeland Security(DHS)



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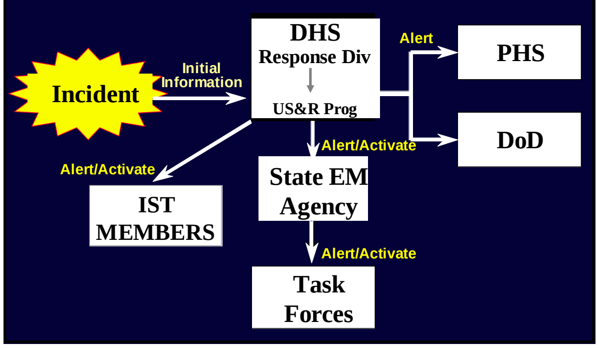
DHS/FEMA Notification Process



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National Response Framework

- 15 Emergency Service Functions
  - Search & Rescue is ESF-9
  - US&R is only small part of total Federal Response
  - DHS/FEMA provides many other post disaster help to State and Local Governments
- Requirements of implementing NRF
  - Presidential Declaration
  - Cost Sharing 75-25 to 100-0
  - Federal Accountability

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Typical Disaster Organization

- DHS/FEMA HQ - EST
- DHS/FEMA Region - ROC
- Disaster Field Office - DFO
  - All appropriate ESFs represented
  - Federal Coordinating Officer - FCO
- State and Local Emergency Operations Centers – EOC
  - May be collocation of some offices
- Local Incident Commander IC
  - DHS/FEMA US&R works in support of IC
  - Memorandum of understanding
  - Operate under Incident Command System

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DHS/FEMA US&R Response Sys

- 28 Task Forces
- System Goals/Direction Setting Groups
  - Advisory Committee
  - Task Force Leaders
- System decision making process
  - US&R Division Director
  - Operations Group
  - 12 Working Groups
    - K9 and Structures Sub-groups

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DHS/FEMA US&R Objective

- Location, Rescue (Extrication), & Initial Medical Stabilization of Victims Trapped in Confined Spaces

from

- Earthquakes, Hurricanes, Tornadoes, Explosions, Terrorist Acts and other Life Threatening Disasters

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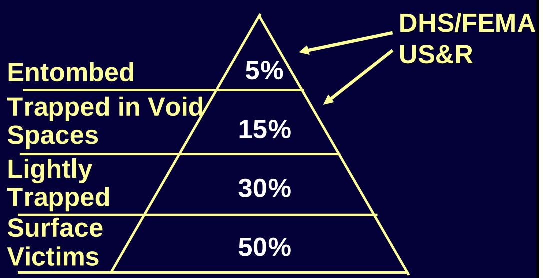
Disaster Victim Classification



The Most Effective Response is the Most Local, since it's the Most Timely

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Survival Rates of Trapped Victims

Earthquakes

30 minutes	90% survive
1 day	80% survive
2 days	40% survive
3 days	30% survive
4 days	20% survive
5 days	10% survive

Requires Rapid US&R Deployment and Response – Influences Risk vs Reward

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Survival Rates of Trapped Victims in Blast Incidents

- No Live Victims have been recovered from collapse zone of a blast Incident following Day 1
- Has significant effect on Risk vs Reward Evaluations
- Effects transition from Rescue to Recovery Operations

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National US&R Response System History

- Impetus for US&R System - 1990
  - Loma Prieta Quake and Hurricane Hugo (1989) highlighted the natural threats in the U.S. and underscored the need for a National US&R capability.
  - Subsequent history has modified the focus to include Terrorism Threats
  - Initial “Only Live Victim Rescue” has been expanded to “Returning all Victims to their loved ones”

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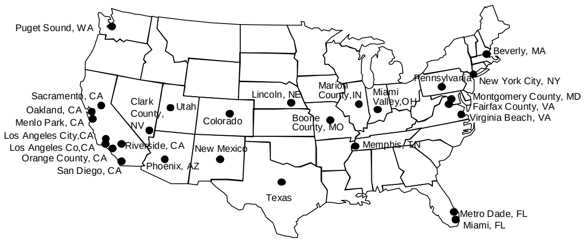
Today’s US&R Task Forces



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Today’s US&R Task Forces

- Each Task Force Team has 70 Personnel
  - *10 additional support for over highway
- Each TF is Three Deep for Each Position
- Equipment Cache of ~$2.5 Million
- Rigorous Training Schedules
- Type 1 has 70 Personnel* – Standard TF
- Type 2 has 70 Personnel – WMD, Special
- Type 3 (Light TF) has 28 Personnel

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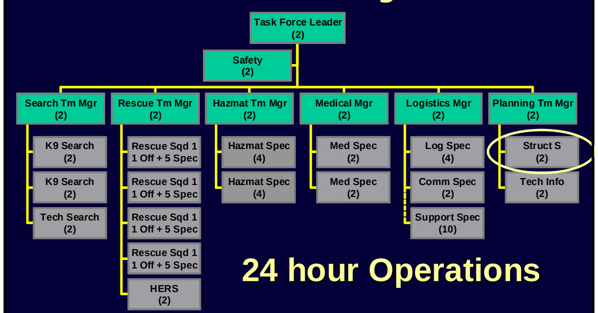
70 Person - Task Force Organization



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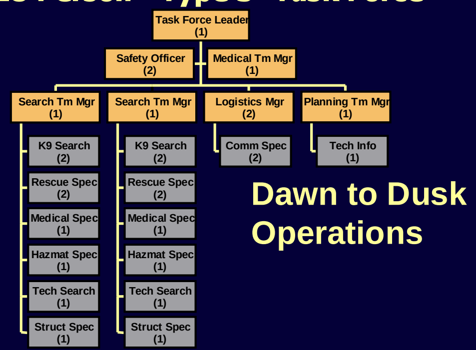
28 Person - Type 3 -Task Force



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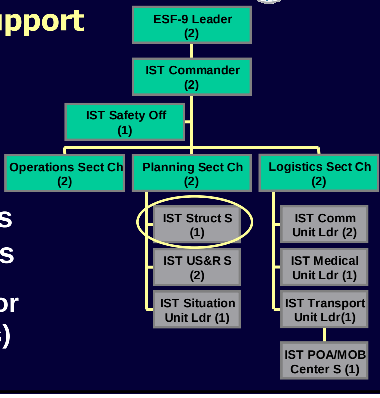
Incident Support Team - A



20 Positions
24 Hour Ops

(may add 6 for full 24 hr ops)

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US&R Task Force Operational Guidelines

- 24-hour Operations
- Two 12-hour Shifts (except initial Blitz Mode)
- Self-sufficient for 72 Hours
- Re-supply after 72 Hours
- Reports to Point of Departure within 6 Hours of Activation
- Multi-faceted/Cross-trained Personnel
- Standard Equipment and Training
- Uses Incident Command System
  - Support Local Incident Commander
  - StS MUST work within system

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DHS/FEMA US&R Events

- 1992, Hurricane Andrew
- 1992, Hurricane Iniki
- 1992, Typhoon Brian
- 1993, Hurricane Emily
- 1994, Northridge Quake
- 1995, Oklahoma City
- 1995, 3 - Hurricanes
- 1996, Hurricane Fran
- 1996, Puerto Rico Gas Exp
- 1998, Kansas Grain Elevator Explosion
- 2001, World Trade Ctr
- 2001, Pentagon
- 2002, Winter Olympics
- 2003, Hurricane Isabel
- 2004, 3 - Nat Sec Events
- 2004, 4 - FL Hurricanes
- 2005, 4 - Gulf Hurricanes
- 2006, TS Ernesto
- 2007 & 8, 4- Hurricanes
- 2009 Earthquake or Explosion???

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National US&R Response

Principal Event History

- 1985 Mexico City Earthquake
  The Beginning
- 1990 DHS/FEMA Starts US&R
- 1994 Northridge Earthquake
  The System is somewhat tested
- 1995 Oklahoma City Bombing – *Terrible event, but comprehensive test of system*
- 9/11 Attacks – System was Overloaded
- Katrina – System not well enough prepared

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Mexico City Earthquake

- 1985
- 10,000 Dead
- 150 Rescue Workers Dead
- Many untrained rescuers
- 1st U.S. Foreign Response

Genesis of Urban Search & Rescue

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Northridge Earthquake

- 1994
- 1st Test
- Activated 10 Task Forces
- Deployed 3 local Task Forces

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Oklahoma City

- 1995
- 11 Task Forces for a total of 15 days (max 7 days for an individual Task Force)
- Recovered 168 victims
- Experience created improvements in Task Force Ops
- 37 StS Deployed

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World Trade Center

- 9-11-2001
- 24 Task Forces – 22 days (max 8 days for Task Force)
- Provided aid to FDNY
- Difficult and unique experience, following the loss of 343 firefighters
- Risk / Reward was a victim
- 62 StS deployed
- SEAoNY Response

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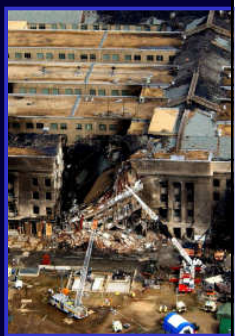
Pentagon

- 9-11-2001
- 5-DHS/FEMA TFs + 3 Local Rescue Units - 9 days
- Unified Command within well controlled site
- Good cooperation with other US&R forces and Contractor
- Good management of Risk
  - Recovery on Day 5
- 15 StS deployed



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Katrina, Ophelia, Rita

- 29Aug05
- 2 BoO, LA & MS
- Initially 2-IST, 5-TF , + 5-TF in Reserve
- All 16 CA Boats
- Eventually all 28-TFs, some 2x
- DHS/FEMA Logistics overwhelmed
- Support by USCG
- Re-assess priorities
- Hurr Rita, overreaction

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2006 & 2008 Hurricanes

More robust pre-deployment

- 2006 Ernesto – Pre-deployment & Training
  - IST + 5 TF in Atlanta
  - IST + 5 TF in Jacksonville
- 2008 Gustav, Hanna, & Ike
  - Initially 2 - IST + 12 TFs in various locations from Atlanta to Houston
  - Some TFs were away from home for 21 days
  - Some were deployed for 1 or 2 days in Galveston/Houston area
  - Difficult impact on TF members lives

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US&R Task Force Capabilities - 1

- Physical, Canine, and Electronic Searches
- Rescue Ops in various types of structures:
  - Wood Frame & Steel Frame
  - Reinforced Concrete & Precast Concrete
  - Unreinforced Masonry & Unreinforced Concrete
- Advanced Life Support Medicine,
  - Specializing in Crush Syndrome
- Structural Integrity Assessments & Mitigation
- Hazardous Materials Assessments & Referral
  - Rescue and mitigation possible for WMD TFs

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US&R Task Force Capabilities - 2

- Coordination with Heavy Equipment Operations
- Communications Capabilities
- Logisticians for Resource Accountability, Maintenance, and Procurement
- Technical Documentation Development
- Public Information Capabilities
- Incident Action Planning

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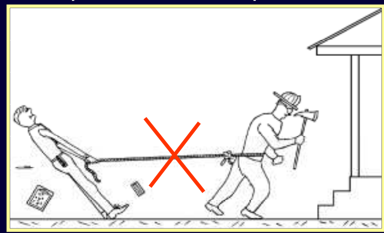
Why Structures Specialists?

- Not to Impede Rescue Operations,



- Rather, to promote lower risk Rescue Ops

StS for short

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US&R Focus

- DHS/FEMA US&R Objectives
  - Locate, Rescue & Medically Stabilize Victims
  - Focus on VICTIMS
- StS Responsibilities
  - Support the above US&R Objectives
  - Focus on RESCUERS

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The Structures Specialist

- ADVISOR to T F Leadership
- Technical Resource with no Direct Authority to start or stop Search and Rescue Operations
- The relationship between the StS and the other T F members is critical
- Respect for each other's Positions, & confidence in other's duties is:
  Accomplished through TRAINING TOGETHER!

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StS Development History

- Training developed by USACE in 1991
  - USACE augments and supports DHS/FEMA US&R
  - USACE received funding from DHS/FEMA & DoD
  - Two decades development, training, & support
- USACE US&R Program
  - Training for DHS/FEMA, USACE, State & International StS
    - Yearly StS1, StS2 and Regional Training
  - Train & maintain USACE StS Cadre
  - Employs the StS Training Cadre
- Prerequisite is P.E. or Equivalent

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Overview of StS Roles

- The Structures Specialist will typically be assigned to one of the following positions:
  - Task Force Structures Specialist– DHS/FEMA, USACE & State Certificated StSs are eligible for this role. Some State US&R TF have USACE Certificated StS
    - Number of DHS/FEMA TF StS = about 160
    - Number of USACE StS = about 60
    - Number of USACE Certificated, State StS = more than 100
  - US&R Incident Support Team (IST) Struc Specs Selected DHS/FEMA StSs are eligible for this role
    - Number of US&R IST StS = about 12
    - USACE StSs provide technical support to the US&R IST StS.

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What is Rescue Engineering?
What is expected of a StS?

- Very different from "Office Engineering"
  - No Computer, No Staff, No Quiet Space
  - No time to Study Problem & "Get Back"
  - No "Orderly Problem" – No Comfort Zone
- It is "NOW" Engineering"
  - Need to "See Through" the disorderly Structure
  - Need to "Recognize" the critical structural issues
  - Need to "Prioritize" your tasks
  - Need to "Recall" previous, similar incidents
  - Need "Quick References" in your Head
  - Need to "Respond" Quickly & Creatively
  - Need to "Understand" Risk – Reward progression
  - Expect to be "Uncomfortable"

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StS Tasks
Task Force
Personnel Safety

- Risk of collapse or injury
- Access to Victims
- Egress & Safe Havens
- Risk/Reward

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StS Tasks
Evaluate Damaged Structures

- Rapid Structure Recon/Assessment
- Classification of Building Type and Collapse Risks
- Monitoring During Operations
- Building Marking

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StS Tasks
Hazard Mitigation

- Avoid & Minimize Risk Exposure
- Stabilization of Structure
- Shoring for Access to Voids
- Heavy Rigging Picks
- Rubble Removal
- Creative Alternatives

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General Requirements

- Able to function safely at heights and on or around rubble.
- Maintain current inoculations
- Be available on short notice to mobilize within six hours of request for a response assignment of up to 10 days in austere environments.
- Working knowledge of ICS.
  - StS Must work within ICS System
  - ICS 100, 200, 700, 800

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General Requirements - Training

- Current CPR Certification
- DHS/FEMA US&R Orientation
- Respiratory Protection Training
- DOJ Emergency Response Training
- Complete WMD Enhanced Ops
- Complete of GPS Awareness Level
- Complete Operations Level For HazMat
- Complete Awareness Level Per NFPA 1670:
  - Confined Space Operations
  - Water Rescue Operations
  - Structural Collapse Operations

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Requirements for StS, Specific - 1

- Currently licensed as a Civil Engineer specializing in Structures or Equivalent
  - Struct Sub-group determines equivalency
- A minimum of five years experience in structural design and analysis to include evaluation of existing structures, field investigation or construction observation experience.
- Expertise in Structures

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Requirements for StS, Specific - 2

- Ability to identify vertical load and lateral force resisting framing systems and the critical elements within those systems.
- Ability to identify failure indications of building materials.
- Understand the behavior of Wood Structures
- Ability to identify building features that could provide entry or access to victims such as ducts, shafts, etc.
- Able to recommend practical solutions for US&R operations in compromised structures.

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StS Specific Training

- Structures Spec.Course StS1
  - DHS/FEMA US&R & Risk vs. Reward
  - Building Systems and Collapse
  - Hazard I.D. & Mitigation
  - DHS/FEMA Shoring Systems
  - Heavy Equipment & Rigging
  - Rapid Reconnaissance
  - DHS/DHS/FEMA Disaster Site Marking System
- Continuing Education
  - Advanced StS Training – StS2
  - Total Station & GPS
  - StS Tools & Rescue Skills

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StS job is to not let this Happen!!!

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Hazard Assessment & Mitigation Techniques for Collapsed Buildings

Presentation:
Michael G. Barker, PhD, PE, U of Wyoming, USACE StS, formerly MO-TF1

Paper Authors:
Michael G. Barker, U of Wyoming
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David J. Hammond, Chair, SSG, DHS/FEMA
Thomas R. Niedernhofer, USACE

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Everybody is asking the Structures Specialist!!

- Is this a GO or NO-GO?
- Is it Safe to be working in this area?
- What is the Chance of that falling?
- What is the Safest way to enter?
- Where are we Likely to find Voids?
- What can we do to the Reduce Risk?
- What type of Shoring should we build?
- Where is the Progressive Collapse Zone?

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Structures Specialist in DHS/FEMA US&R

- FEMA US&R Objectives
  - Locate, Rescue & Medically Stabilize Victims
  - FOCUS ON VICTIMS
- StS Responsibilities
  - Support the Above US&R Objectives
  - FOCUS ON RESCUERS
- The survival of victims and fellow response personnel may depend on StS Judgment

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Critical StS Roles at Disaster Site

- Identify & Assess Hazards
- Mitigate Hazards to an Acceptable Level of Risk

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Hazard Assessment & Mitigation Problems

- Judgments cannot be precise
- Partially collapsed structures difficult
- Collapsed structure has come to rest, but it is now weaker and more disorganized than original structure
- Damage may have caused partial collapse, but building remainder may be weakened & ready to collapse with additional demands

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The Structures Specialist

- Uses knowledge of building systems
- Experience from training and other disaster work
- Understands capabilities of US&R personnel
- Operates within the Incident Command System

To

- Provide the best advice on the risks and managing those risks during search & rescue operations

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Assessing Hazards

- Collapse Hazards
  - Potential energy level
  - Failure modes and effects analysis
  - Viability of Vertical & Lateral Load Paths
  - Ductility & Redundancy
- Falling Hazards
- Other Hazards
  - Environmental, WMD
  - Secondary devices
- Hazard during assessment & mitigation

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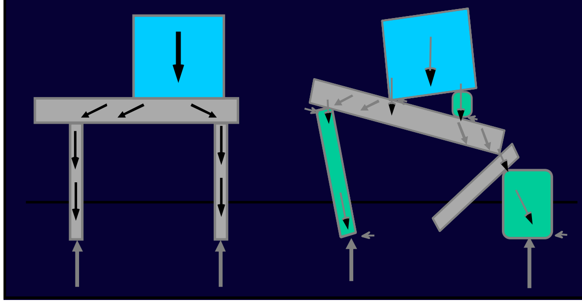
Structure/Hazard Assessment



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3 Story, Offset Earthquake Collapse

StS tasked with Assessment for US&R

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Adjacent roof, no redundancy Lean-To Collapse

Corner Bldg w/Front & Prop Line Wall Fall

Where are Victims?
What are Hazards?

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Mexico City Earthquake
10 story Type C1 Concrete
Outer bay floors collapsed

How to reduce risk for Searching Building?
Point of entry & safe havens?

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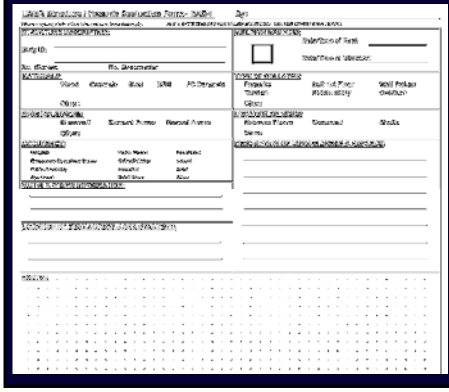
Puerto Rico Steel Frame Gas Explosion

Light Floor "Lift & Drop." Columns Pushed out at Beam Connection

How to Mitigate falling and collapse hazards?



US&R Forms:

HAZ-1

HAZ-2 is large sketch area

Structure/Hazard Assessment

- What caused the collapse?
- Has structure collapsed to a stable condition?
- Identify vertical & lateral systems
- Brittle or ductile behavior
- Check for redundancy
- Check for potential instabilities
  - Building stability
  - Rubble stability

Structure/Hazard Assessment

- Visualize what could happen during additional demands
- What if there is additional demands - what is the plan? (safe haven areas / escape routes)
- Before changing the existing configuration (mitigation/rubble removal), evaluate the effect on the Load Path
- Can the hazards be mitigated to an acceptable level? What is risk during mitigation?

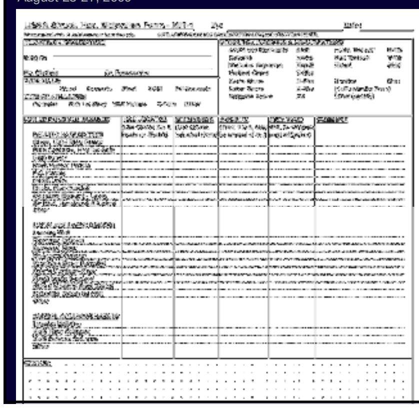
Hazard Mitigation

Hazard Mitigation

- Following assessment, the StS considers alternatives that will reduce risk for US&R Ops
- Mitigation Plan is essential component of risk vs reward analysis
  - Mitigation will normally be done in a series of steps
  - As Reward of finding live victims decreases, additional mitigation should be planned and implemented to further decrease the risk to rescuers
  - Mitigation may be planned as a continuum that reduces risk, step by step
  - Hazards of implementing mitigation needs to be considered

Hazard Mitigation Techniques

- Short-Term, Quick Mitigation
  - Avoid & Barricade
  - Remove (if easy)
  - Minimize Exposure
  - Spot Shoring
  - Monitoring (for immediate needs)
- Longer-Term, Resource Intensive Mitigation
  - Developed Shoring Systems
  - Remove (if difficult)
  - Monitoring (for long-term needs)
- US&R Forms: MIT 1



US&R Form MIT-1

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Simple Hazard Mitigation

- Avoid
  - Need effective barrier system
  - May be lowest risk option
- Removal
  - Lift off, push over, pull down
  - Operation may require Site Evacuation
  - May pose some risk to hidden victims

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Simple Hazard Mitigation

- Exposure reduction
  - Risk is a function of severity and exposure
  - How long do personnel need to be in the area?
  - Limit time exposed to hazard
  - Limit number of personnel exposed
  - Can be a short term, high risk option

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Hazard Mitigation

- Immediate need, short-term or longer-term Monitoring
  - Plumb Bob
  - Crack Gage
  - Smart Level
  - Laser Level
  - Total Station
  - Wireless Building Monitoring System

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Hazard Mitigation

- Short-term or longer-term Shoring
- Vertical & Lateral Shoring
  - Place Shoring and progressively upgrade shoring capacity and stability as operations continue
    - Class 1, Spot Shores
    - Class 2, Two-dimensional Shores
    - Class 3, Interconnect pairs of Class 2 to form three dimensional Shores

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Class 1 – Class 2 – Class 3

T Shore – 2 Post Vertical – Laced Post

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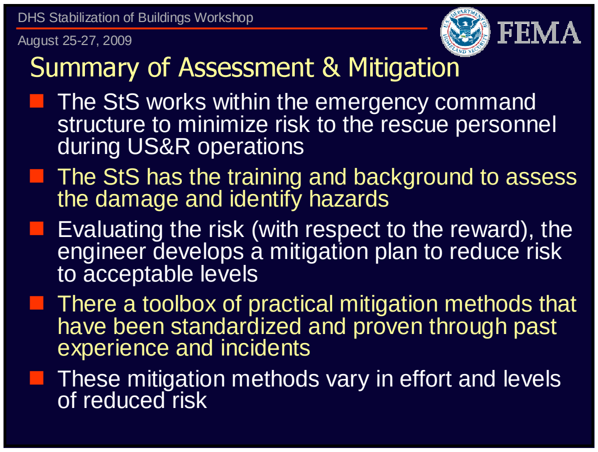
Lateral Bracing & Shores

Column Bracing **Building Bracing**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Summary of Assessment & Mitigation
The StS works within the emergency command structure to minimize risk to the rescue personnel during US&R operations
The StS has the training and background to assess the damage and identify hazards
Evaluating the risk (with respect to the reward), the engineer develops a mitigation plan to reduce risk to acceptable levels
There a toolbox of practical mitigation methods that have been standardized and proven through past experience and incidents
These mitigation methods vary in effort and levels of reduced risk

Why Buildings Fail? The Basics, and Beyond!

DHS Workshop on Stabilization of Buildings

Vicksburg, MS

Mohammed M. Ettouney, Ph.D., PE, MBA, F.AEI

August 25, 2009

Outline

- Definition of 'The Basics'
- Theory of Progressive Collapse
- Concepts of Building Stability
- On the Types of Buildings
- The 'Beyond'
- Closing Remarks

Definition of 'The Basics'

- Those issues that have major influence in stability of buildings
  - Or partial buildings (those parts of the building that remain standing after an IED attack, or other abnormal events, such as an earthquake)

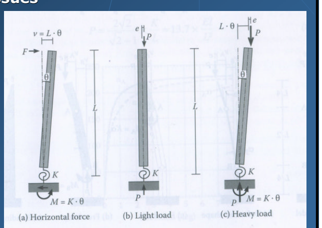
Theory of Progressive Collapse

- Theory of progressive collapse were introduced in 2003 describes the problem in a simplified fashion
- ***When an initiator event causes a local failure in a building, the resulting failure front will propagate through the structure until the failure front is arrested, or until the remaining structure becomes geometrically unstable.***
- The challenge is to investigate the stability of REMAINING building

Concepts of Building Stability

- Euler's equation describes completely ALL building stability issues

$$P_{cr} = \frac{\pi^2 E I_c}{(K H)^2}$$



The 'I'

- Technically: Moment of Inertia
- Generally: Foot print of building
- When too much of the foot print fail, the building is prone to be unstable
- Thus buildings with larger foot print are inherently more stable

The 'E'

- Technically: Represent the stiffness of the building
- Generally: Can also represent the state of mechanical properties of the building
- For example, after fire, the 'E' can be degraded enough to render the building unstable!
- Also, after a bombing attack, the 'E' can be reduced enough to render the building unstable!

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The 'KH'

- Refers to height
  - Of building
  - Of floors
- Or combinations of same
- As 'KH' increase, the building, or component, becomes more prone to being unstable.

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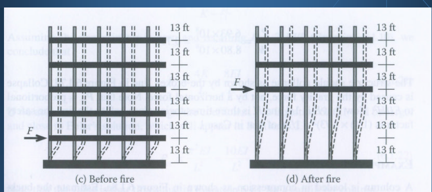
The 'KH'



- When a fire destroyed few floors in a high-rise in NYC
- The height (KH) of the columns increased far beyond the design allowance
- The build became unstable, and eventually collapsed in its entirety!

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The 'KH' + 'I' Combinations

- Tall buildings (KH) with small foot print (I) are susceptible to instability problems

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The 'PI'

- Simply stated: not all building types (or remainders of buildings after an initial collapse) are created equal
- Some structural systems are 'more stable' than others
- Which bring us to 'Types of Buildings'

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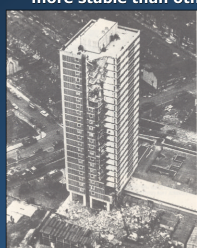
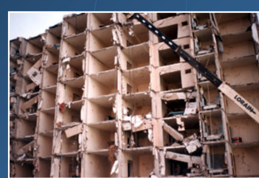
On the Types of Buildings - 1

- Bearing walls buildings are inherently more stable than other types of buildings





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On the Types of Buildings - 2

- Next comes shear walls (concrete), or braced frames (steel)
  - Assuming that enough redundant systems are available, which are not usually the case!

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On the Types of Buildings - 2

- Next come framed (columns + beams) buildings
- The most studied type
  - Even though it is not the most widely used,
  - or the most efficient from stability view point!

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The 'Beyond'

- There are immense knowledge gaps in the field of engineering for stabilization of buildings
- Among which:

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Modes of Failure

- Dynamics of columns
- Dynamics of axially loaded walls

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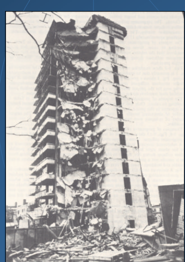
Partial Failures

- Design of partially collapsed (or partially yielded structures
- Not considered even in the field of earthquake design of building!



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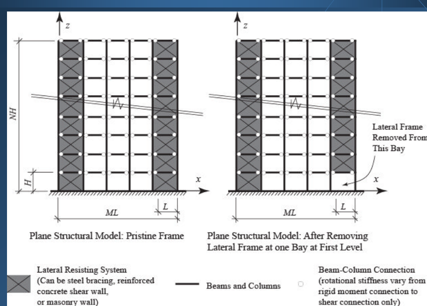
Partial Failures - 1



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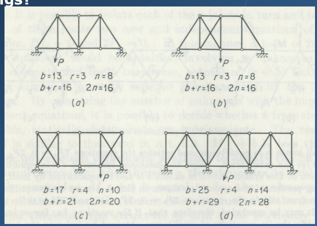
Redundancies!

- How to quantify redundancy in buildings?
- How to quantify redundancy in partially collapsed buildings?



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Nonstructural components

- Role of nonstructural components in stabilizing, or destabilizing, of buildings
  - Envelope
  - Partitions
  - Etc…

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Component vs. System Design

- Structural Analysis community have been analyzing structural systems since the inception of 'structural analysis'
- However, in Design, the story is very different!
  - We do not design for systems!
  - That should change!

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Uncertainty Principles

- Role of uncertainty in building stability issue

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QUESTIONS?

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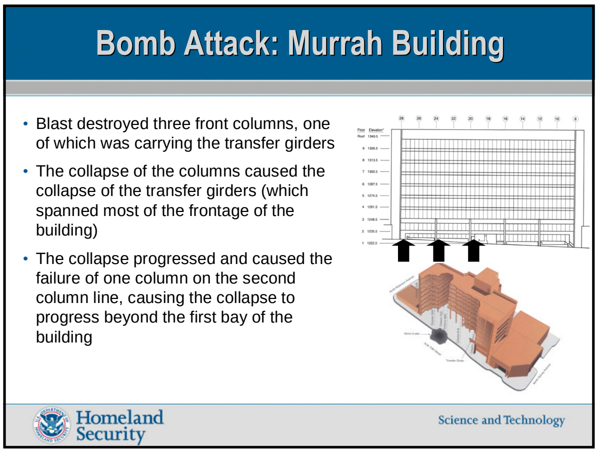
Concepts of Advanced Engineering
Roles of ultra-performance structures:
A new way of thinking after 9/11
Eric Letvin
URS Corporation
July 28-29, 2009
Singapore
Homeland Security
Science and Technology


Bomb Attack: Murrah Building
• Blast destroyed three front columns, one of which was carrying the transfer girders
• The collapse of the columns caused the collapse of the transfer girders (which spanned most of the frontage of the building)
• The collapse progressed and caused the failure of one column on the second column line, causing the collapse to progress beyond the first bay of the building
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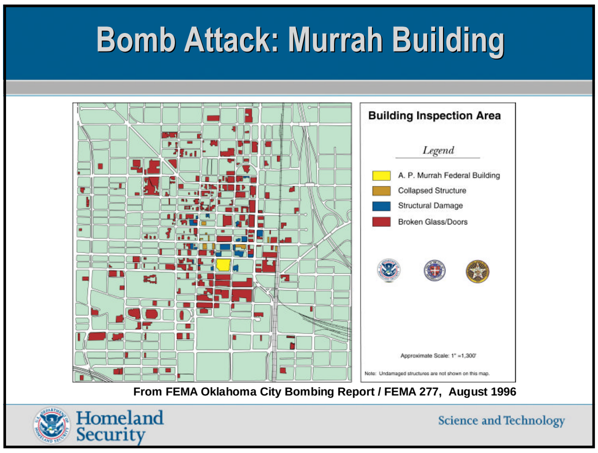
Bomb Attack: Murrah Building
Building Inspection Area
Legend
A. P. Murrah Federal Building
Collapsed Structure
Structural Damage
Broken Glass/Doors
From FEMA Oklahoma City Bombing Report / FEMA 277, August 1996
Homeland Security
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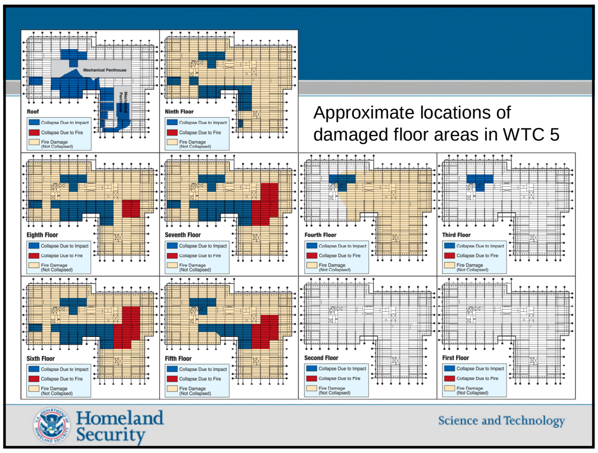
Marriott Hotel after collapse of WTC
Homeland Security
Science and Technology

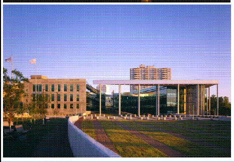

Homeland Security
Science and Technology


Approximate locations of damaged floor areas in WTC 5
Roof
Ninth Floor
Eighth Floor
Seventh Floor
Fourth Floor
Third Floor
Sixth Floor
Fifth Floor
Second Floor
First Floor
Homeland Security
Science and Technology

Concepts of Advanced Engineering: Roles of ultra-performance structures

Eric Letvin

Advanced Materials and Lessons Learned



Laminated Glass

- Two annealed sheets with a thick PVB interlayer
- Interlayer keeps glass in the frame in case of blast

Blast Wall

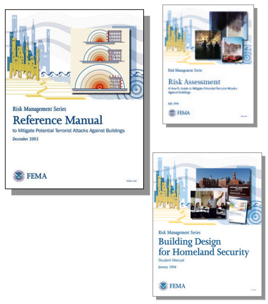
- In addition to a 50-foot setback, blast-resistant concrete walls protect those portions of the building that face the street.

Opened November 2003
(No Government Law enforcement tenants)

Homeland Security — Science and Technology

DHS Security Guidelines

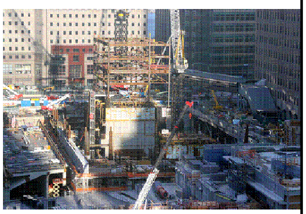
- Specific building design guidance for high-risk buildings or explosive blast, fire and chemical / biological / radiological threats.
- DHS offers these recommendations, which are not legally compulsory, as a step toward the more systematic inclusion of security considerations in the building design process.
- Federal, state, local government, design professionals and law enforcement use these guidance to help influence infrastructure design.



Homeland Security — Science and Technology

One World Trade Center

- Construction Began April 2006
- 1,776 feet
- 102 stories
- Standoff on west side increased from 25 feet to average of 90 feet in June 2005 due to concerns raised by NYPD
- Windows on the side facing the street will have special blast film



Homeland Security — Science and Technology

One World Trade Center

- Structural redundancy
- 3 feet (91 cm) thick walls for all stairwells, elevator shafts, risers, and sprinkler systems inside central core
- Advanced life-safety systems including dense fireproofing, extra-wide pressurized stairwells, additional stair exit locations, and emergency lighting
- Extra stair wells for rescue workers and a dedicated communication system
- Chemical / biological filters in air supply system

Homeland Security — Science and Technology

One World Trade Center

- 187 foot concrete base
  - First 30 feet are completely solid
  - Next 50 feet have some openings for light
  - Rest of base is occupied by mechanical floors
- Concrete base clad with steel and titanium panels covered by blast resistant glass prisms for aesthetics

Homeland Security — Science and Technology

Future – what will regulate building design?

- Building Codes?
- Insurance? ASCE - BSC
- Safety Act?
- Standard of Care?

Homeland Security — Science and Technology

Concepts of Advanced Engineering: Roles of ultra-performance structures
Eric Letvin

Fire & Building Stabilization

Najib Abboud, Chad McArthur, Darren Tennant & Mohammed Ettouney

Fire & Building Stabilization

Najib Abboud, Chad McArthur, Darren Tennant & Mohammed Ettouney

DHS & ERDC Stabilization of Buildings Workshop
Vicksburg, MS
August 25-27, 2009

WEIDLINGER ASSOCIATES, INC.

NEW YORK MASSACHUSETTS CALIFORNIA WASHINGTON,DC NEW JERSEY NEW MEXICO UNITED KINGDOM

Stability of buildings on fire

- Special Challenge to the Stability of Buildings on Fire: the TIME element. The "Event" (load) is still unfolding and evolving while first responders are on the scene.
- First Responders must be able to assess whether to:
  - Pull out and stop fighting the fire
  - Affect a full building evacuation
  - Clear the neighboring area ie determine the size of the collapse zone
- 9/11 graphically displayed how poorly attuned our rescue operations are to this load. Can we expect anything different in a major earthquake?

Degradation of structural steel

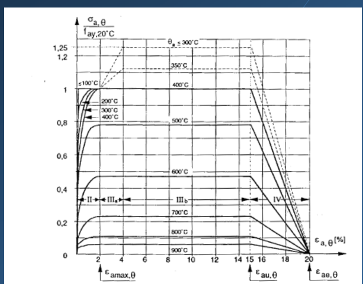


Fig. A.2: Graphical presentation of the stress-strain relationships of structural steel at elevated temperatures, strain-hardening included.

Ref: Eurocode ENV: 1994-1-2:1994

Degradation of siliceous concrete

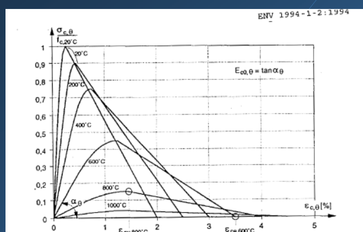
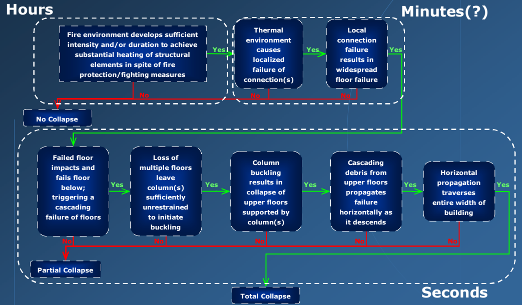


Fig. B.1: Graphical presentation of the stress-strain relationships for siliceous concrete with a linear descending branch, including the recommended values $\varepsilon_{cu,\theta}$ and $\varepsilon_{ce,\theta}$ of table B.1.

Ref: ENV: 1994-1-2:1994

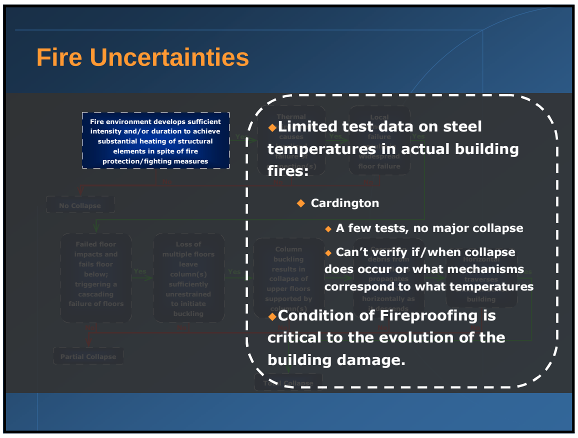
Example Fire Induced Collapse: Steel frame building

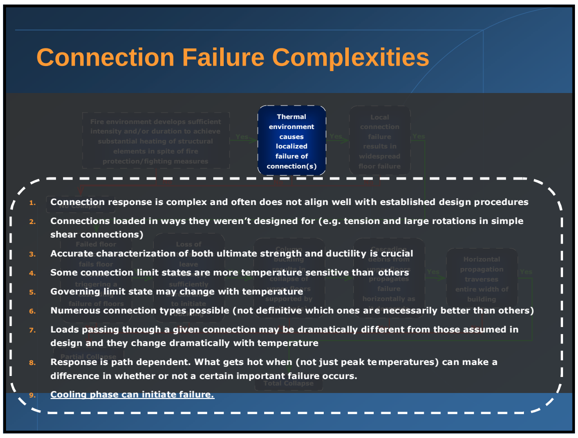


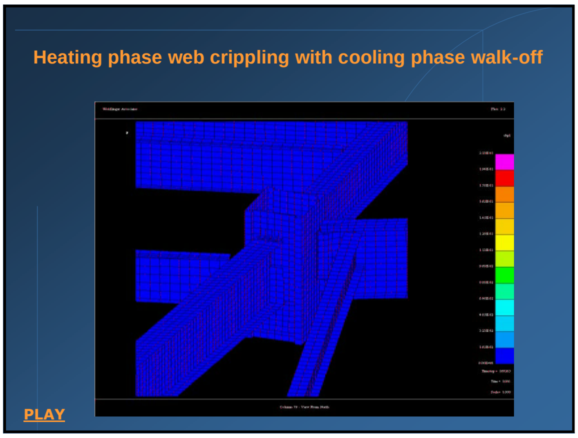
Notes on the previous slide

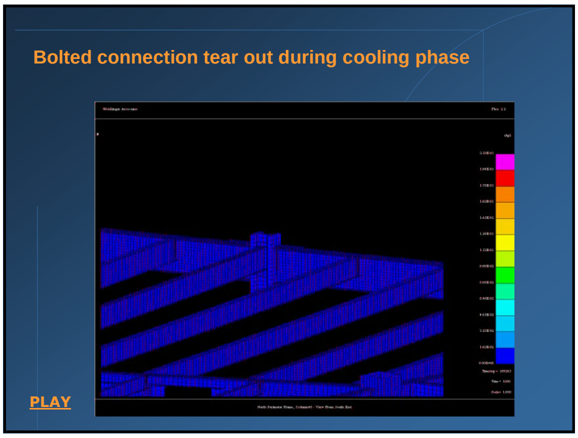
- In this example, note that multiple conditions must be satisfied in order for total collapse to be achieved.
- The primary mechanisms of collapse are connection failure and column buckling.
- Slab behavior can play a unique role in failure propagation that is not explicitly expressed in the flow chart
- Depending on building-specific features, this example hierarchy could be re-arranged or portions could be short-circuited (e.g. failure of lateral system due to direct fire attack or collateral damage from partial collapse).
- Quantification of the important phenomena at each step carries considerable uncertainty. Accumulation of uncertainties as the path progresses can draw final conclusions into question.

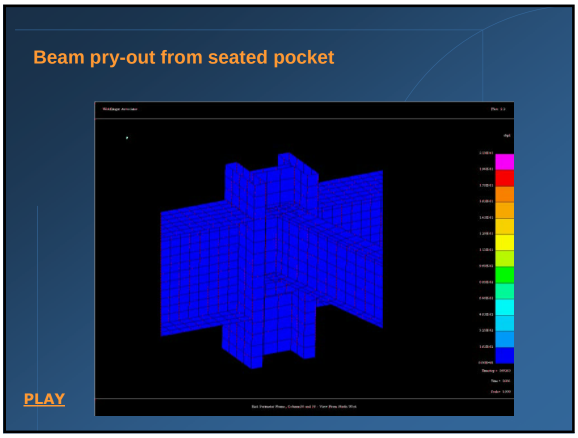
Fire & Building Stabilization
Najib Abboud, Chad McArthur, Darren Tennant & Mohammed Ettouney

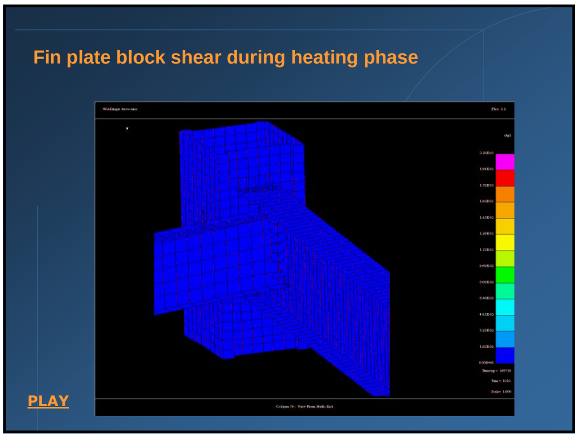












Fire & Building Stabilization
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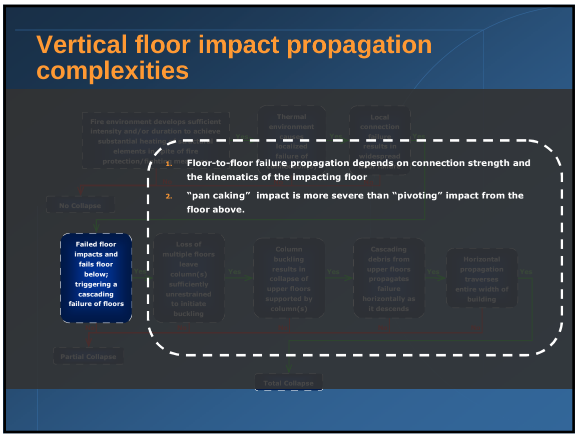
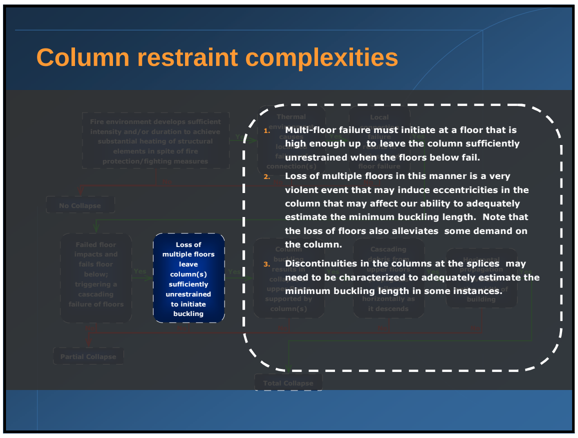
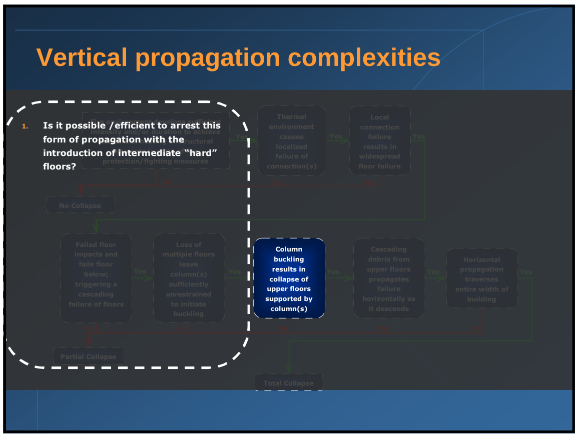
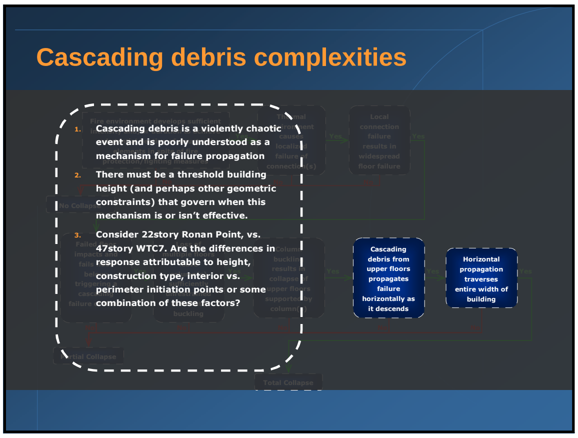
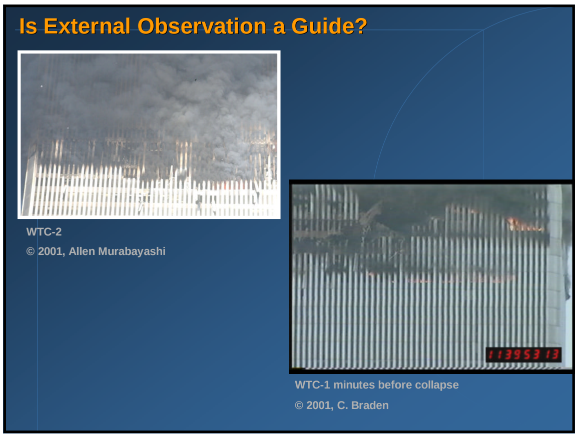










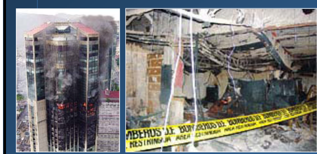
Can We Acquire Internal Data?

- What data do we need. Unsure but:
  - Thermal environment
  - Floor Deflection & current structural damage
  - Condition of fireproofing
  - Internal Visuals

Do Visuals Help?

1 Meridian Plaza

Cardington: Failure during fire (top) and during cooling (bottom)



Caracas Plaza
Caracas Plaza

Can We Interpret Data?

- Currently, we can only interpret data accurately as part of a forensic exercise.
- We do not have a sufficient base of case studies, let alone relevant ones, to start recognizing “signatures” of a structure heading towards collapse.
- We do not have a sufficient base of case studies to postulate size of collapse zones

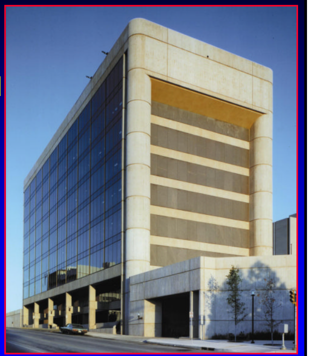
NEED:

- To develop a reliable dataset of simulated buildings on fire:
  - Building & Construction Types
  - Fire Types
- Conduct a data analysis to find “signatures” and to develop answers pertinent to first responders operations.

Blast Response of a Seismically-Retrofitted Reinforced Concrete Building

Presented By:

Stanley C. Woodson, PhD, PE



Background/Introduction

- FEMA 277, The Oklahoma City Bombing: Improving Building Performance Through Multihazard Mitigation

  "Many of the techniques used to upgrade the seismic resistance of buildings also improve a building's ability to resist the extreme loads of a blast and reduce the likelihood of progressive collapse following an explosion …"

- Related Activities
  - Federal agency surveys of seismic safety in existing buildings
  - 9/11/01

Objectives

- Work on the question: "Does seismic strengthening improve blast/progressive collapse resistance?"
- *Not* the same question as "Is seismic design the same as blast design?"
- Evaluate Murrah Building for High Seismicity location.
- Strengthen building for improved earthquake performance, with no specific consideration for blast resistance.
- Re-detail original frame as Special Moment Frame per ACI 318-02 (no new lateral force analysis).
- Perform blast and progressive collapse response analyses of "new" systems in same manner used for FEMA 277.

FEMA Project Team

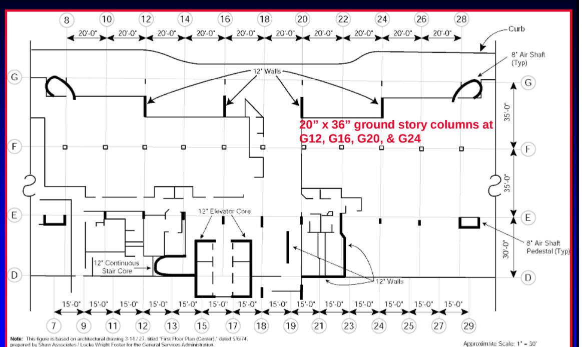
- FEMA (Morelli, Mahoney, Hanson): Sponsor
- Degenkolb Engineers (Poland, Pekelnicky): Seismic analysis and design; cost estimates
- ERDC GSL (Woodson): Blast response analysis
- CTL (Corley) and Purdue University (Sozen): Peer review and technical oversight
- ERDC CERL (Hayes): Management and integration

Brief Review of FEMA 277

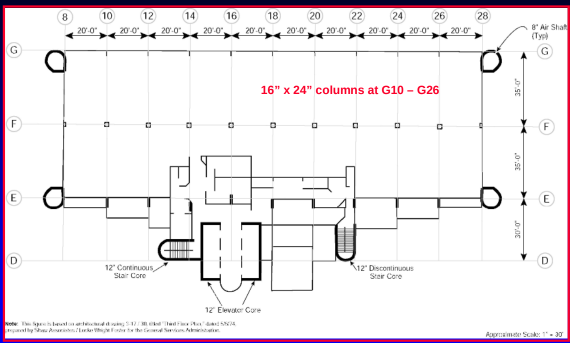
Building constructed ca 1974-1976

Main office building: 9-story R/C frame + shear wall structure

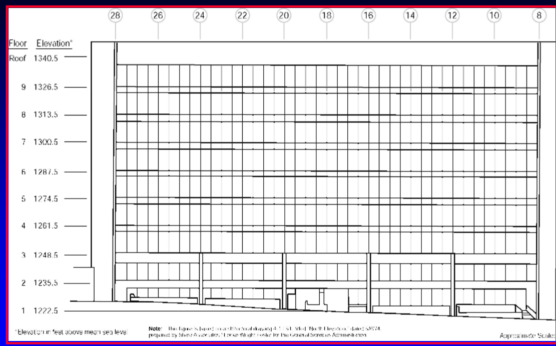
Main building surrounded on 3 sides by 1-story office buildings and parking structure



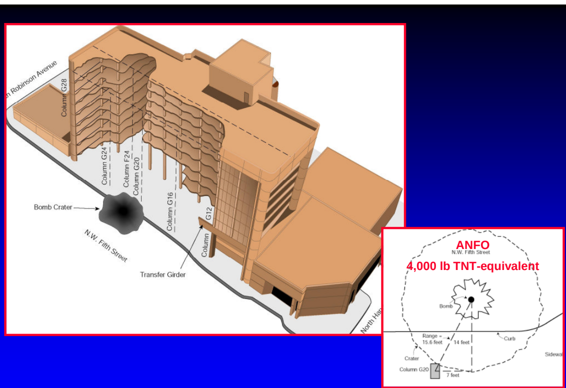
1st Floor of Original Building



3rd Floor of Original Building

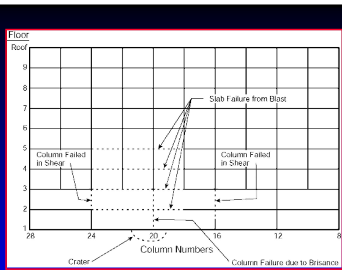


North Face Elevation of Original Building



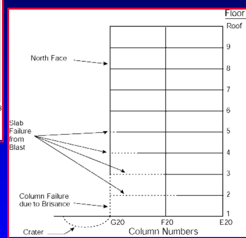
Blast and Progressive Collapse Damage to Original Building

Schematic Diagrams of Blast Damage in Original Building



North Face Elevation

- Total Building Floor Area: ~ 137,800 SF
- 4% (~ 5,850 SF) destroyed by blast
- 42% (~ 58,100 SF) destroyed by blast + progressive collapse



North-South Section

Seismic Evaluation

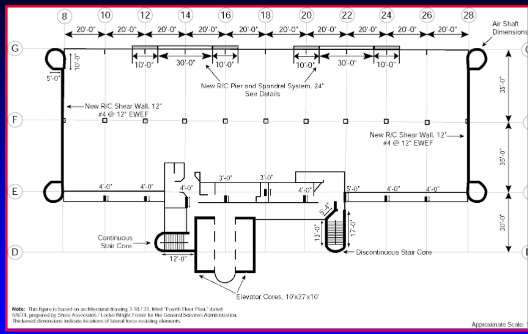
- High Seismicity: 7th and Mission Streets, San Francisco
- ASCE 31-02, ***Seismic Evaluation of Existing Buildings***
- Tier 1 Screening (checklist)
- Tier 2 Evaluation
- Tier 3 Detailed Evaluation , reference FEMA 356, ***Prestandard and Commentary for the Seismic Rehabilitation of Buildings***
- Major Findings:
  – Detailing inadequate for Life Safety (rebar lap splices, element confinement)
  – Excessive shear stresses in core walls
  – Torsional irregularity (asymmetric shear walls)

Strengthening Schemes for Improved Earthquake Resistance

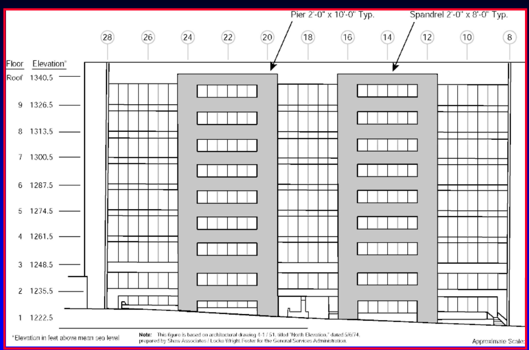
- Transverse: 12” lightly reinforced concrete shear walls between ventilation shafts at east and west ends of building
- Longitudinal
  1. Pier-Spandrel System on North Face
  2. Special Moment Frame on North Face
  3. Interior Shear Walls
  4. Re-detailed frame system IAW ACI 318-02 (no lateral force analysis)

Pier-Spandrel System

- 2 – 24” thick R/C Pier-Spandrel walls on north face
- 10’ wide piers
- 8’ deep spandrels
- Dowel into existing north face frame
- Founded on existing column caissons
- Preserve much of original window openings
- Estimated cost: $2.37M



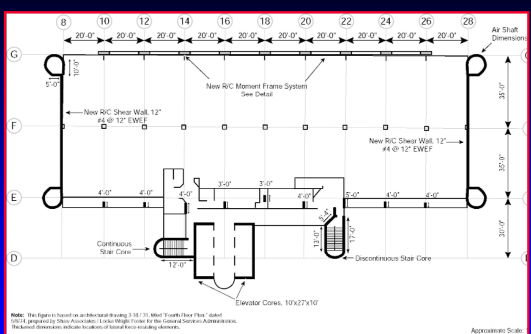
Typical Floor Plan for Pier-Spandrel System



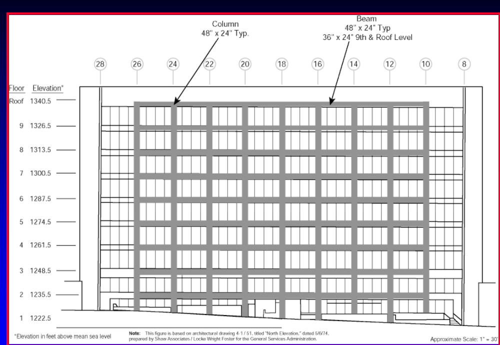
Elevation for Pier-Spandrel System

Special Moment Frame System

- 24” x 48” columns on north face
- 24” x 36” beams on north face (9 Fl, Roof)
- 24” x 48” beams on north face (8 Fl, below)
- Dowel into existing frame
- Founded on existing column caissons
- Estimated cost: $3.64M



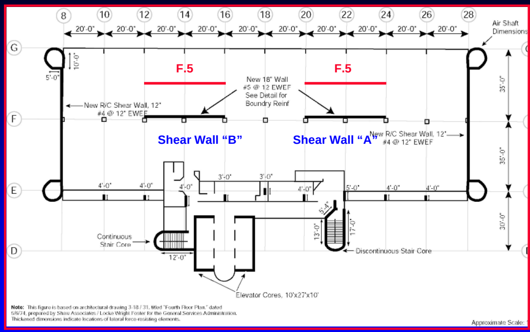
Typical Floor Plan for Special Moment Frame System



Elevation for Special Moment Frame System

Interior Shear Wall System

- 2 full-height walls on Line F
- 2 bays each
- 18” thick, lightly reinforced
- Boundary elements
- Dowel into existing columns
- Founded on existing column caissons
- Estimated cost: $1.95M
- Alternate location: Line “F.5”
  - Estimated cost: $2.30M



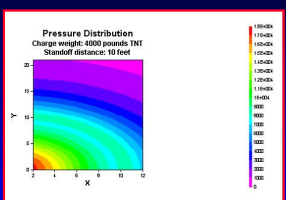
Typical Floor Plan for Interior Shear Wall System
(“F.5”Location Shown in Red)

Re-detailed SMF System

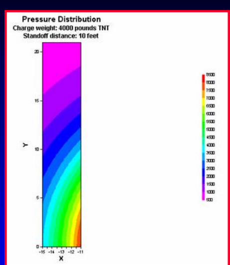
- Increased transverse & longitudinal reinforcement
- More continuity in longitudinal reinforcement
- Increased column sizes for strong column – weak beam behavior (e.g. 45” x 36” at ground story)
- No lateral load analysis

Blast Response Analyses

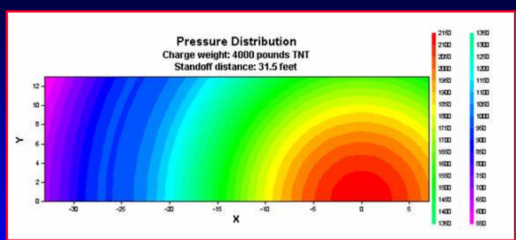
- *ConWep*: Blast load generation
  - Actual reflected pressure & impulse
  - Idealized uniform reflected pressure & impulse
  - Breaching analysis
- *Span32* and *WAC*: SDOF response
  - Based on uniform pressure loading
  - Based on yield line analysis
  - Provides mid-span deflections



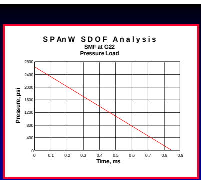
Reflected Pressure Distribution on Pier G20
Pier-Spandrel System



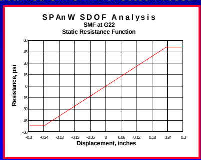
Reflected Pressure Distribution
1st Story Column G22
Special Moment Frame System



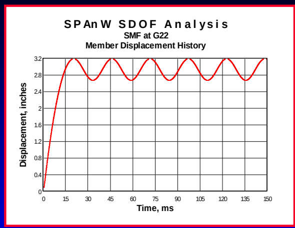
Reflected Pressure Distribution on 1st Story Shear Wall A



Idealized Uniform Reflected Pressure



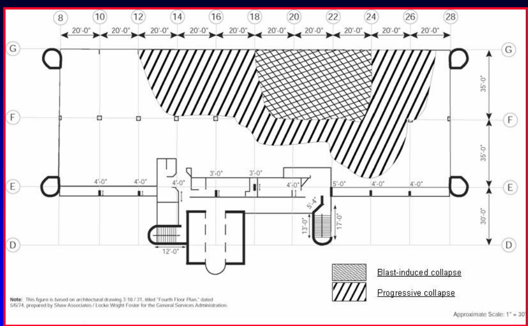
Element Resistance Function



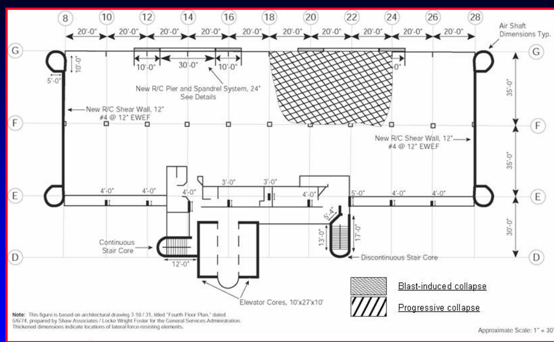
Predicted Mid-Span Response

Progressive Collapse Analyses

- Floor slabs not strengthened in any scheme
- Blast-damaged members removed before analysis
- Gravity + 25% Live Load
- Elastic analysis followed by plastic mechanism analysis
- Based on assumption that impact loads are twice static loads, examine Capacity/Demand (C/D):
  - If C/D > 2, then no collapse
  - If 1 < C/D < 2, then examine more closely and assess
  - If C/D < 1, then assess as failed

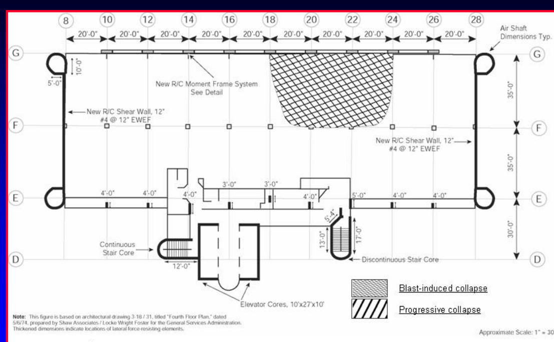


Damage to 3rd Floor Level
Original Building



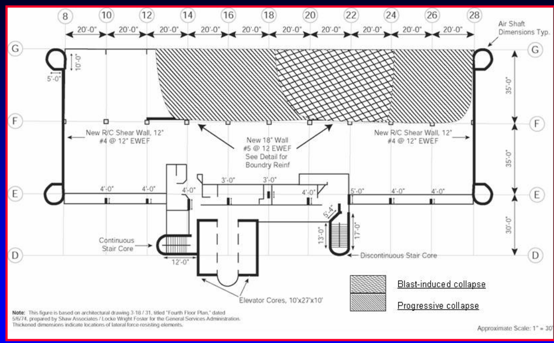
Estimated Damage to 3rd Floor Level
Pier-Spandrel System

Estimated Damage for Pier-Spandrel System

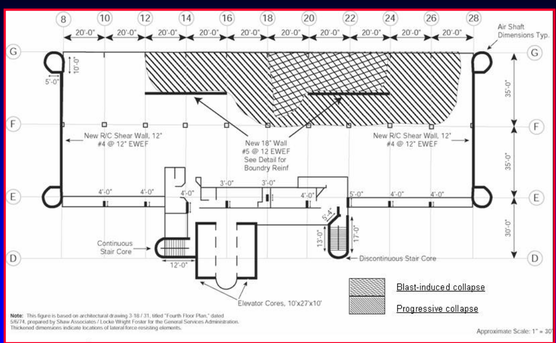


Estimated Damage to 3rd Floor Level
Special Moment Frame (SMF) System

Estimated Damage for SMF System



Estimated Damage to 3rd Floor Level
Interior Shear Wall System – Line F



Estimated Damage to 3rd Floor Level
Interior Shear Wall System - Line F.5

Estimated Damage for Interior Shear Wall System - Line F

Floor Level	Floor Area (SF)	Blast Damage (SF)	Progressive Collapse Damage: Original Building (SF)	Pier-Spandrel Scheme (SF)	SMF Scheme (SF)	Shear Wall Scheme – Line F.5 (SF)	Shear Wall Scheme – Line F (SF)
Roof	15,200	0	6,300	0	0	4,650	5,250
9th	15,200	0	6,300	0	0	4,650	5,250
8th	15,200	0	6,300	0	0	4,650	5,250
7th	15,200	0	6,300	0	0	4,650	5,250
6th	15,200	0	6,300	0	0	4,650	5,250
5th	15,200	300	6,300	300	300	4,650	5,250
4th	15,200	1,050	6,300	1,050	1,050	4,650	5,250
3rd	15,200	2,100	7,000	2,100	2,100	4,650	5,250
2nd	15,200	2,400	7,000	2,400	2,400	6,150	5,250
Total	137,800	5,850	58,100	5,850	5,850	43,350	47,250
% of Total Floor Area Damaged		4%	42%	4%	4%	31%	34%
% of Damaged Area Due to Blast		-	10%	100%	100%	12%	12%
% of Damaged Area Due to Progressive Collapse		-	90%	0%	0%	88%	88%

Estimated Damage Based on Floor Area

Conclusions

- Pier-Spandrel, Special Moment Frame, and Re-detailed Systems significantly improved blast and progressive collapse resistance.
- Interior Shear Walls modestly improved blast and progressive collapse resistance.
- Strengthening an existing R/C building to meet high seismic demand will improve its blast and progressive collapse resistance.
- Providing high seismic zone detailing for a building will improve its blast and progressive collapse resistance.
- It is more efficient for external blast and impact resistance to place elements proportioned and detailed for seismic forces on the building perimeter.

Analysis Techniques for Assessing Structural Damage

Larry McMichael and Lee Glascoe

Analysis Techniques for Assessing Structural Damage

DHS Workshop on Building Stabilization

Vicksburg, MS

Larry McMichael, Ph.D., Lee Glascoe, Ph.D., PE

August 25, 2009

LLNL-PRES-416100

Lawrence Livermore National Laboratory

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Acknowledgements

- **This presentation reflects a variety of efforts performed by the Engineering Directorate, Science and Technology Principal Directorate and Global Security Principal Directorate at LLNL.**
- **Includes contributions from an extended, multi-disciplinary team:**
  - Chad Noble, Ph.D., Joseph Morris, Ph.D., Steven Alves, Ph.D., Jonathan Margraf, Yunwei Sun, Ph.D., Ian Darnell, Ph.D., Edwin Kokko, Alan Lamont, Ph.D., Vera Bulaevskaya, Ph.D., Michael King, Ph.D., Ana Kupresanin, Ph.D.

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Overview

- **LLNL's perspective**
  - Techniques align with available capabilities and resources
- **General approaches**
  - Threat independent system analysis
  - Component level failure
  - System level blast analysis
- **Stochastic simulations**
  - Characterize uncertainty
  - Fast-running analysis tools
- **Improving predicted material response**
  - Material characterization
  - Multi-scale methods
- **Summary**

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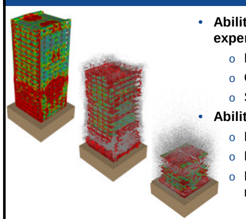
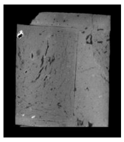
Multi-disciplinary team approach using state-of-the-art experimental and computational resources



- **Ability to draw from a wide variety of subject matter experts:**
  - Engineers (civil, mechanical, computer science)
  - Geoscientists (soil/rock failure, ground motion)
  - Statisticians (stochastic methods)
- **Ability to provide end-to-end system analysis:**
  - Nondestructive material characterization
  - Explosive test facilities
  - High fidelity simulations (Lagrangian, ALE, meshless methods)
- **Leverage DOE investment in massively parallel computers and cutting edge finite element analysis software**

Hera Linux Cluster
127.2 TF - AMD;
13,824 processors



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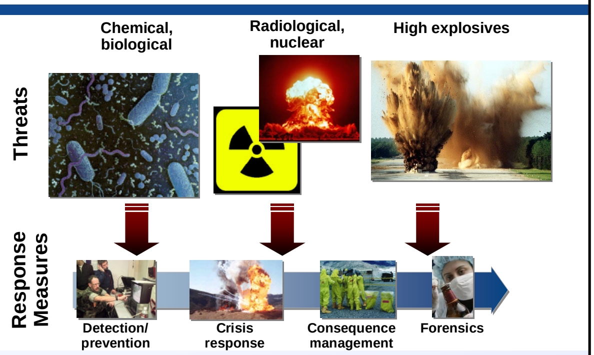
LLNL programs focus on addressing potentially catastrophic threats to critical infrastructure



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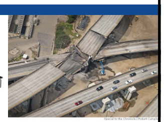
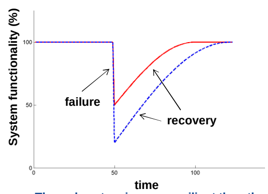
Most structures were not designed to resist blast loads

- **Design decisions based on static and earthquake loads**
- **Blast impulse will exploit any structural weakness**
- **High fidelity simulation plays a key role in improving resiliency**



ParaDyn simulation of the I-880/I-580 MacArthur Maze structural collapse



The red system is more resilient than the blue system.

- **Failure measured as initial loss**
  - Prevention and hardening delays failure
- **Resiliency measured as lost system performance over time**
  - Hardening and redundancy reduces severity of failure
  - Redundancy and response maximizes recovery

Assess vulnerabilities and determine actionable mitigation methods

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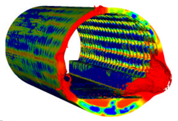
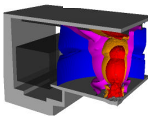
Analysis Techniques for Assessing Structural Damage

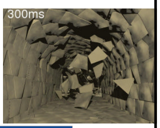
Larry McMichael and Lee Glascoe

Assess structural response to blast loadings

- **Predictive shock and structural failure modeling**
  - o **Vulnerability Analysis**
    - ➢ Hydrocodes and structural codes used to model failure
    - ➢ SPH and soils modeling codes used to predict fluid flow and soil failure
  - o **Mitigation Analysis**
  - o **Uncertainty Quantification**



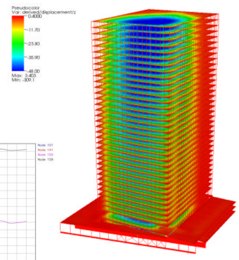


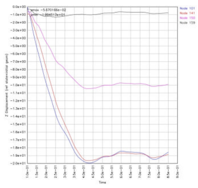


Predict initial component failure and assess ability of damaged structural systems to redistribute loads and prevent structural failure

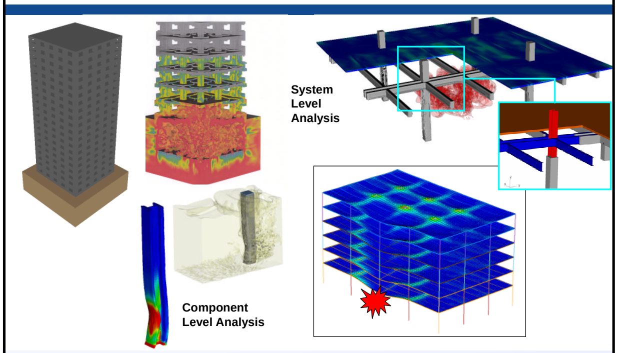
Evaluating structural damage

- **Indicators**
  - o Equivalent plastic strain (EPS) for metals
  - o Damage parameter for concrete models
  - o Residual velocity
- **Extent**
  - o How big of a region is affected
- **Structural redundancy**
  - o What load transfer paths are available?
  - o Are they stable under the increased load?
- **Time histories**
  - o Deflections relative to gravity initialization



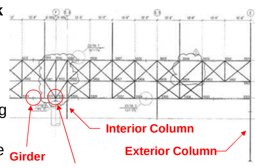


Structural failure can be modeled using threat independent (column removal) or threat specific (fully-coupled blast) analysis



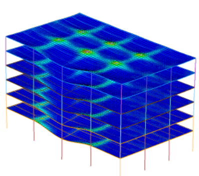
Threat Independent Approach: Identifying Potential Initial Failure Points

- **Structural vulnerability to asymmetric attack is a function of design, construction and environment**
  1. Identify local failures that could initiate progressive collapse
  2. Determine damage propagation and resulting structural stability
  3. Quantify threat required to cause local failure
- **Site and structure dependent**
  - o Perimeter and interior locations
  - o Transitions between structural systems
  - o Connections
- **Threat independent**
  - o Focus on vulnerability, not cause
  - o Consistent with DOD approach (UFC 4-023-03, Design of Buildings to Resist Progressive Collapse)

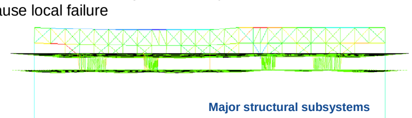


Threat Independent Approach: Determining structural stability

- **Damage propagation leading to progressive collapse**
- **Transient dynamic analysis (DYNA3D, ParaDyn)**
  - o Initial load distribution from static analysis of gravity and service loads
  - o Remove column, girder or connection
  - o Stress waves develop as loads are redistributed
    - ➢ Peak stress will be higher than redistributed steady-state stress
  - o Doesn't account for damage induced by loads that cause local failure



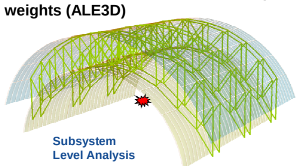
Entire structure



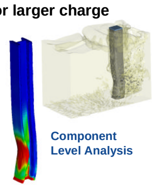
Major structural subsystems

Quantify Threat Required to Initiate Failure

- **Charge weight, stand-off, burst height**
- **Lagrangian materials for larger stand-offs and smaller charge weights**
  - o Fully-coupled blast analysis (ALE3D)
  - o Analytical expression of blast pressures (DYNA3D)
    - – e.g., Kingery & Bulmash equations
    - – Characterized solely by source, no reflected waves from structure or surroundings
- **ALE or Eulerian materials for close proximity blasts or larger charge weights (ALE3D)**



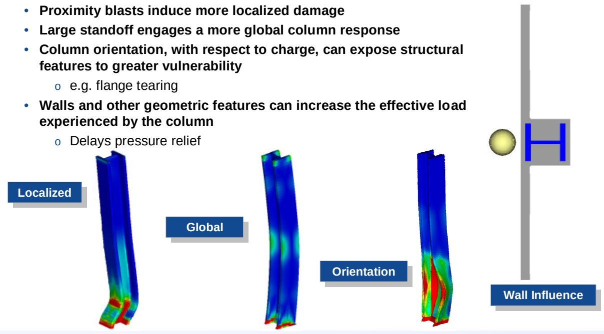
Subsystem Level Analysis



Component Level Analysis

Column Failure Modes are Affected by Charge Location and Surrounding Environment

- Proximity blasts induce more localized damage
- Large standoff engages a more global column response
- Column orientation, with respect to charge, can expose structural features to greater vulnerability
  - e.g. flange tearing
- Walls and other geometric features can increase the effective load experienced by the column
  - Delays pressure relief



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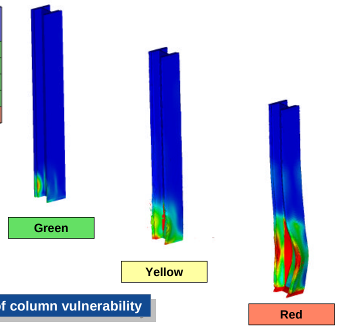
Threat Matrix: Evaluate Column Stability for Various Charge Weights and Standoffs

Strong Axis Orientation	Contact	1 ft	3 ft	10 ft
Weight 1	Green	Green	Green	Green
Weight 2	Green	Green	Green	Green
Weight 3	Red	Red	Green	Green
Weight 4	Red	Red	Red	Green
Weight 5	Red	Red	Red	Red

Weak Axis Orientation	Contact	1 ft	3 ft	10 ft
Weight 1	Green	Green	Green	Green
Weight 2	Yellow	Green	Green	Green
Weight 3	Red	Yellow	Green	Green
Weight 4	Red	Red	Yellow	Green
Weight 5	Red	Red	Red	Red



Useful, but incomplete, picture of column vulnerability

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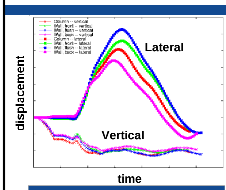
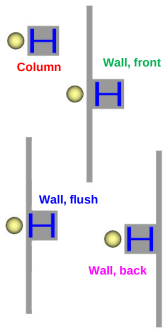
Wall Location Affects Column Vulnerability During Blast

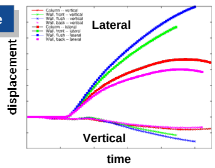


One Foot – Smaller Charge

- Geometric, not strength, effect – Pressure relief
- Wall influence increases as standoff distance moves away from close contact burst



- Vulnerability assessment can change from "Green" to "Red" depending on wall position



Three Feet – Larger Charge

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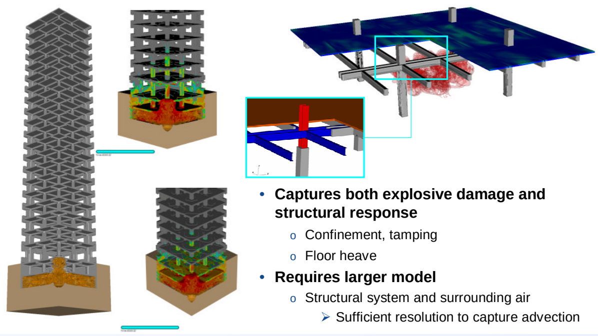
Fully-Coupled Analysis is Necessary when Threat and Explosive Damage is Integral to System Response



- Captures both explosive damage and structural response
  - Confinement, tamping
  - Floor heave
- Requires larger model
  - Structural system and surrounding air
    - Sufficient resolution to capture advection

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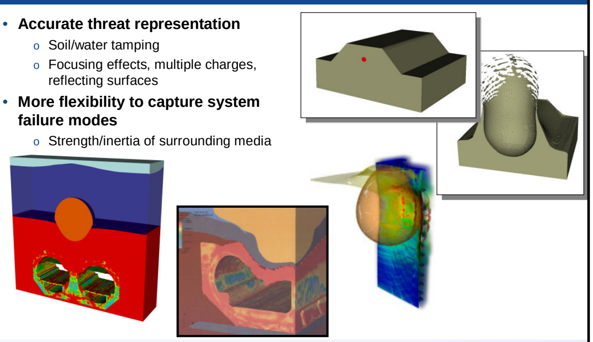
Fully-Coupled Analysis Enables Simulations Beyond Idealized Threats

- Accurate threat representation
  - Soil/water tamping
  - Focusing effects, multiple charges, reflecting surfaces
- More flexibility to capture system failure modes
  - Strength/inertia of surrounding media



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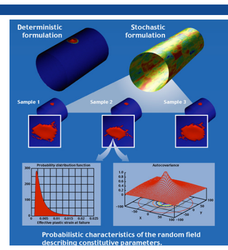
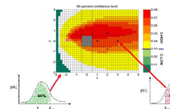
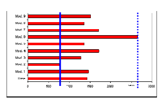
Stochastic Simulation Can Help to Efficiently Utilize High Fidelity Capabilities

- Often too much data and too little time to characterize events and uncertainties
  - Important for highly variable or uncertain conditions
- Advanced stochastic modeling using sampling and discrimination techniques
  - Importance sampling reduces number of simulations required
  - Advanced regression and discrimination techniques to separate/evaluate complex data
  - Provide efficient & probabilistic answers to what? where? when? how much?





Evaluate if failure occurs



Condition on degree of failure

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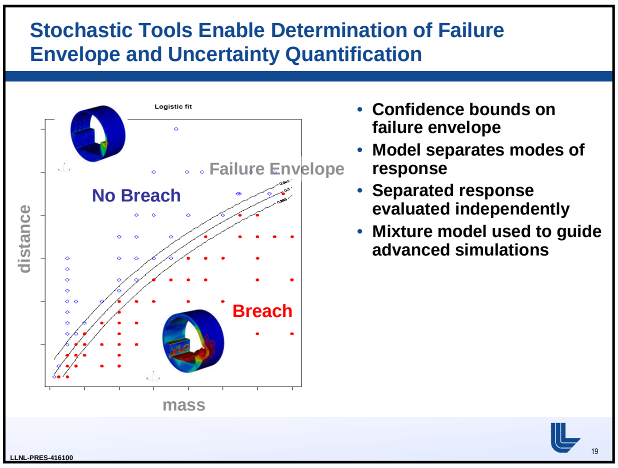
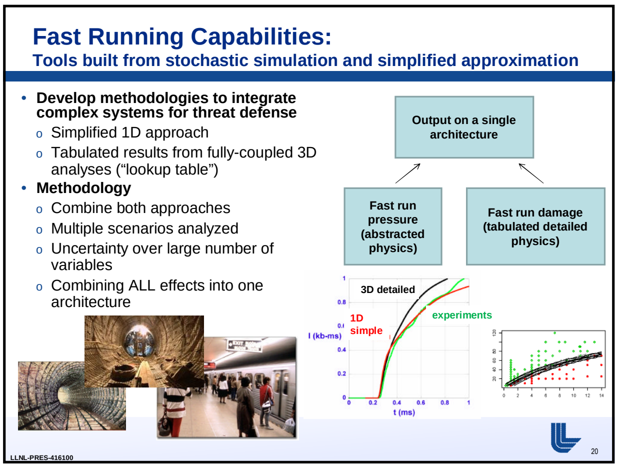
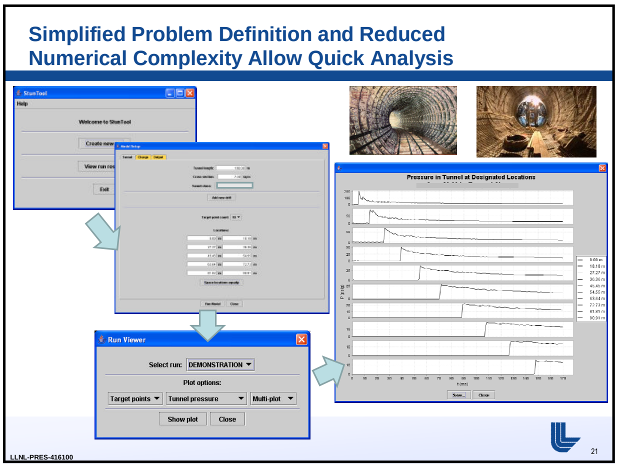
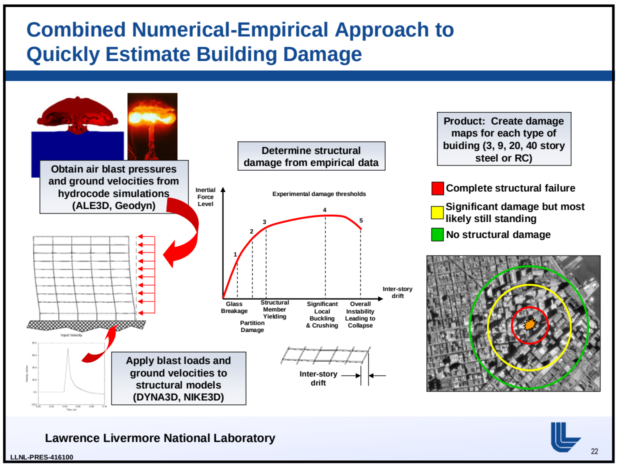
Analysis Techniques for Assessing Structural Damage

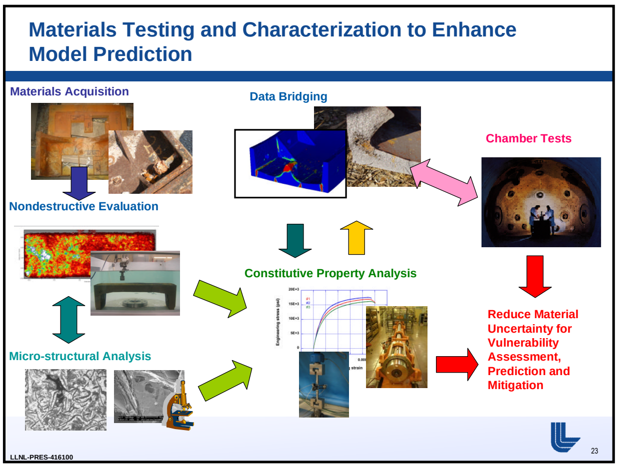
Larry McMichael and Lee Glascoe

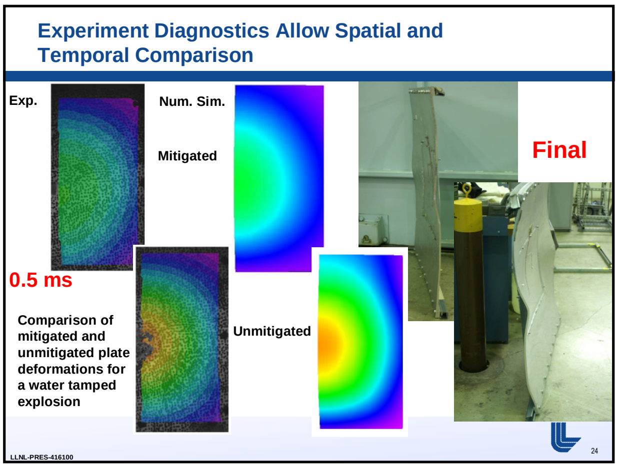


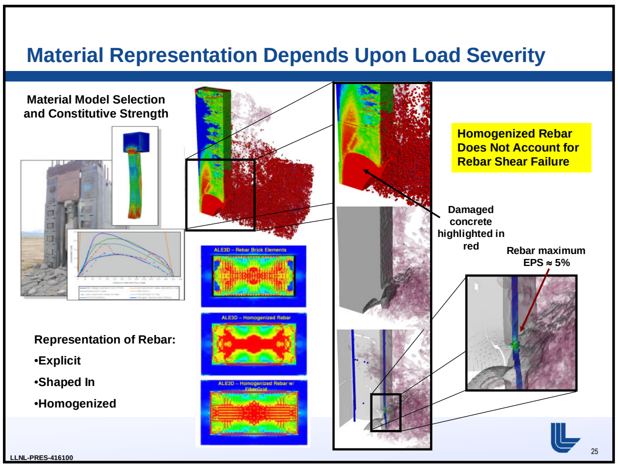











Material Representation Depends Upon Load Severity
Material Model Selection and Constitutive Strength
Homogenized Rebar Does Not Account for Rebar Shear Failure
Damaged concrete highlighted in red
Rebar maximum EPS ≈ 5%
ALE3D – Rebar Brick Elements
ALE3D – Homogenized Rebar
ALE3D – Homogenized Rebar w/ FiberGrid
Representation of Rebar:
•Explicit
•Shaped In
•Homogenized
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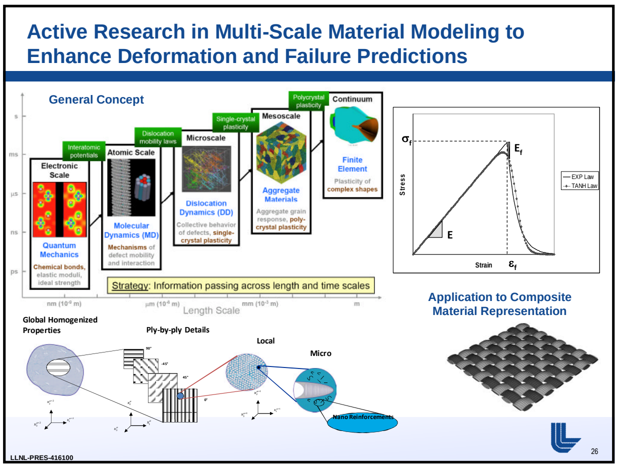
Active Research in Multi-Scale Material Modeling to Enhance Deformation and Failure Predictions
General Concept
Electronic Scale
Quantum Mechanics
Chemical bonds, elastic moduli, ideal strength
Interatomic potentials
Atomic Scale
Molecular Dynamics (MD)
Mechanisms of defect mobility and interaction
Dislocation mobility laws
Microscale
Dislocation Dynamics (DD)
Collective behavior of defects, single-crystal plasticity
Single-crystal plasticity
Mesoscale
Aggregate Materials
Aggregate grain response, poly-crystal plasticity
Polycrystal plasticity
Continuum
Finite Element
Plasticity of complex shapes
s
ms
µs
ns
ps
Strategy: Information passing across length and time scales
nm (10⁻⁹ m)
µm (10⁻⁶ m)
mm (10⁻³ m)
m
Length Scale
Stress
Strain
EXP Law
TANH Law
E
Application to Composite Material Representation
Global Homogenized Properties
Ply-by-ply Details
Local
Micro
Nano Reinforcements
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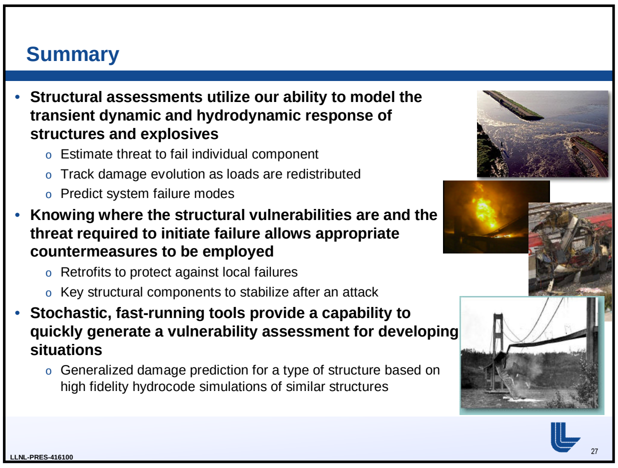
Summary
• Structural assessments utilize our ability to model the transient dynamic and hydrodynamic response of structures and explosives
o Estimate threat to fail individual component
o Track damage evolution as loads are redistributed
o Predict system failure modes
• Knowing where the structural vulnerabilities are and the threat required to initiate failure allows appropriate countermeasures to be employed
o Retrofits to protect against local failures
o Key structural components to stabilize after an attack
• Stochastic, fast-running tools provide a capability to quickly generate a vulnerability assessment for developing situations
o Generalized damage prediction for a type of structure based on high fidelity hydrocode simulations of similar structures
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DHS Stabilization of Buildings Workshop
August 25-27, 2009
FEMA

Shoring Stabilization of Buildings in an Urban Search & Rescue Environment

Presentation:
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Associate, Jacobs Associates
Structures Specialist, CA-TF7 (Sacramento)

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John O'Connell, Collapse Rescue Systems
Thomas C. Clark, P.E., Ironwood Engineering

DHS Stabilization of Buildings Workshop
August 25-27, 2009
FEMA

Building Stabilization Using Emergency Shoring Techniques

Overview

- Objectives of Shoring
- FEMA Vertical & Lateral Shores
- Engineering Methods: Shoring Testing
  - Proof of concepts
  - New configurations

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Assessing the Damaged Structure

- Determine the stabilization objective … rescue, recovery, preservation, or removal
- Consider several options to reduce operating risks
  - Avoid the Hazard
  - Remove the Hazard
  - Minimize Exposure to the Hazard
  - Monitor the Hazard for worsening conditions
  - Shore the Hazard to improve stability
- Emergency shoring demands time, trained personnel & material resources

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Emergency Shoring--

- What Is It?
- Why Use It?
- What are effective shoring techniques

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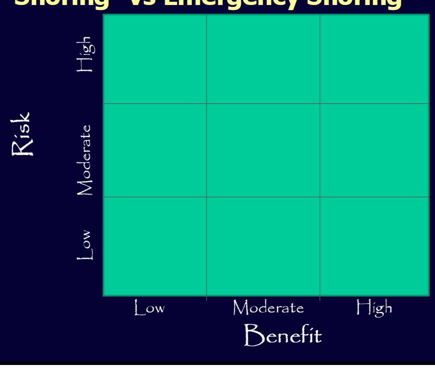
"Shoring" vs Emergency Shoring



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What *IS* Emergency Shoring?

The TEMPORARY SUPPORT of only that part of a damaged, collapsed, or partially collapsed structure that is

REQUIRED for conducting SEARCH & RESCUE operations

AT REDUCED RISK *to the victims and US&R personnel.*

Why Use Emergency Shoring?

- Efficiency
  … Reduce time to patient contact.
  … Optimize available resources
- It is a means to support and redistribute collapse loads, while providing a means to stabilize the immediate area of the damaged structure – especially near victim locations
- Provides structural redundancy and warning of overloads
- Allows rescue operations to proceed at *reduced* risk

Vertical Shore Principles

- Need Posts / Shores with Adjustability & Positive Connections
- Need Lateral Bracing
- Need System with Forgiveness (Ductility and overload warning)

Vertical Shoring Systems

Timber
- Wood Posts
- Window / Door
- Timber cribbing
- Shores for sloped surfaces

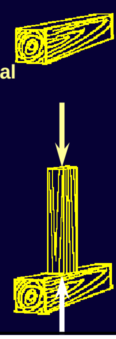
Metal & Mechanical
- Steel Pipe
- Metal Frames & Joist
- Pneumatic Shores

Timber Shores

Seasonal growth in timber develops unique engineering properties which are extremely useful.

Axial Loading
- Slower growth rate in summer deposits more dense fiber
- When loaded parallel to the grain, structural behavior is determined by summerwood
  … Strength with minute deflections.

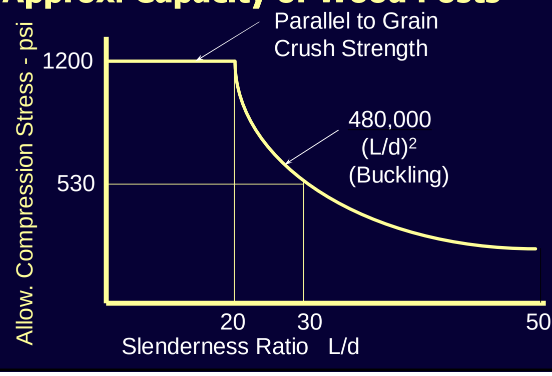
Cross grain Loading
- Rapid growth in spring deposits relatively soft fiber
- When loaded perpendicular to the grain (cross grain), structural behavior is determined by soft springwood
  … Bearing capacity with slow & noisy crushing of springwood



Examples of wood joints with good performance

Good Visual "Fuses"

Approx. Capacity of Wood Posts



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Capacity of Wood Posts

- For L/D to be 25 or Less
  - 4 x 4 should be kept shorter than 8 feet….. 8 kips
  - 6 x 6 should be kept shorter than 12 feet… 20 kips
- Staying < 25 is not always possible
- Reduce L/D with lateral bracing.
  - Bracing must be placed in N-S as well as E-W direction and properly nailed
- US&R shoring uses lots of bracing

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Class 1 Class 2 Class 3

T Shore – 2 Post Vertical – Laced Post

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The Double " T" Shore (Class 2)

- Initial safety shore
- Temporary shoring applications
- More stable than a single "T" shore as a Class 2 shore
- Header length = 36" minimum
- Sole length = 36" minimum
- Posts spaced 18" to 24" out-to-out
- Maximum height is 12 feet

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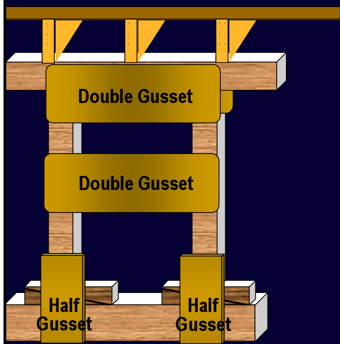
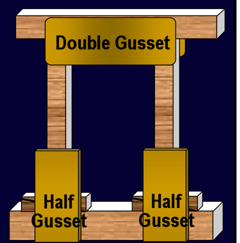
The Double "T" Shore





Less than 6 ft High
No Mid Height Ply Gusset

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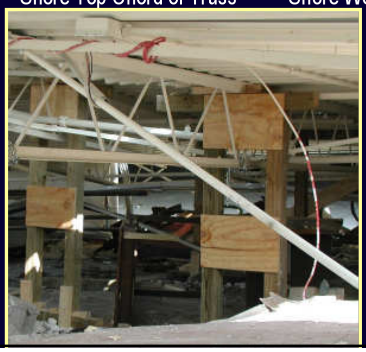
Dbl "T" Shore – simple to install

Shore Top Chord of Truss



Shore Wood Apartment

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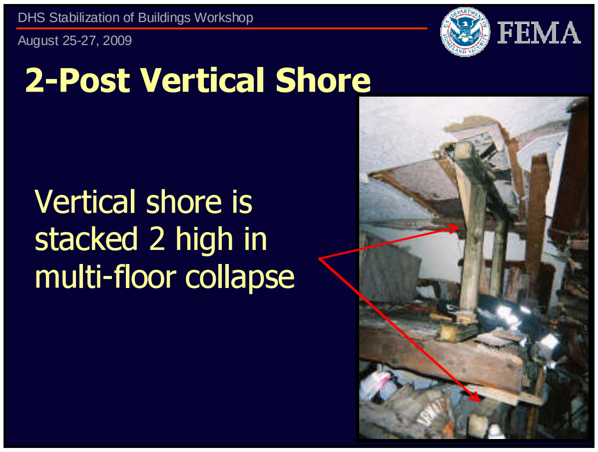
2 Post Vertical Shore (Class 2)

- Faster to build than 3 or 4 post shore
- Same as one side of laced post shore (Can later convert a pair into a Laced Post)
- Use lacing or X-bracing
  Lacing must be 7'-6" max long so it can provide tension & compression capacity
- 4x posts are 4 feet o.c. maximum
- 6x posts are 5 feet o.c. maximum
- Header is 1" min deep for each 1 foot Span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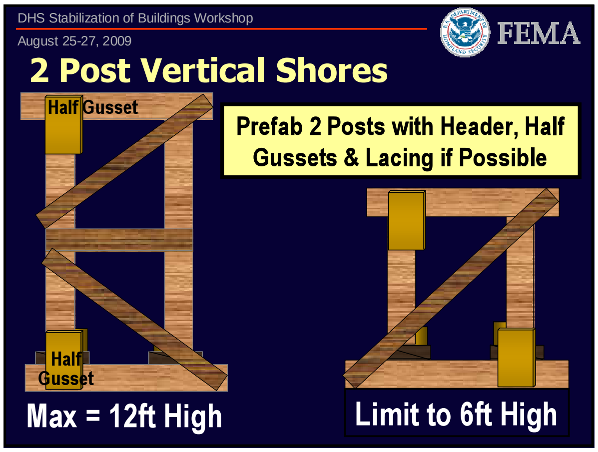
2-Post Vertical Shore
Vertical shore is stacked 2 high in multi-floor collapse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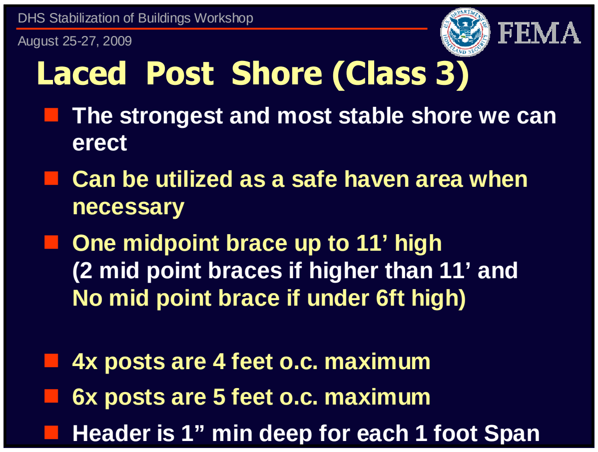
2 Post Vertical Shores
Half Gusset
Prefab 2 Posts with Header, Half Gussets & Lacing if Possible
Half Gusset
Max = 12ft High
Limit to 6ft High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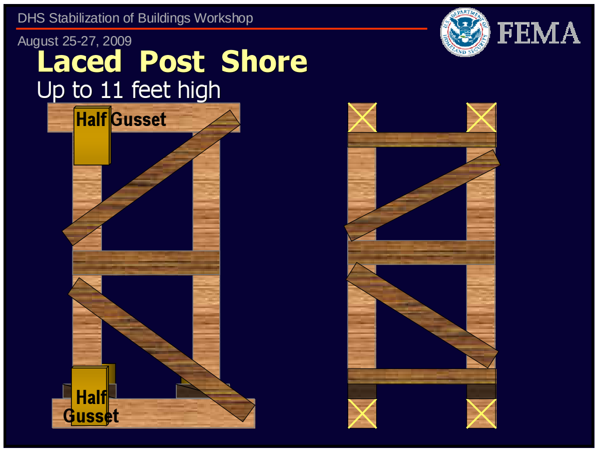
Laced Post Shore (Class 3)
The strongest and most stable shore we can erect
Can be utilized as a safe haven area when necessary
One midpoint brace up to 11' high (2 mid point braces if higher than 11' and No mid point brace if under 6ft high)
4x posts are 4 feet o.c. maximum
6x posts are 5 feet o.c. maximum
Header is 1" min deep for each 1 foot Span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Laced Post Shore
Up to 11 feet high
Half Gusset
Half Gusset


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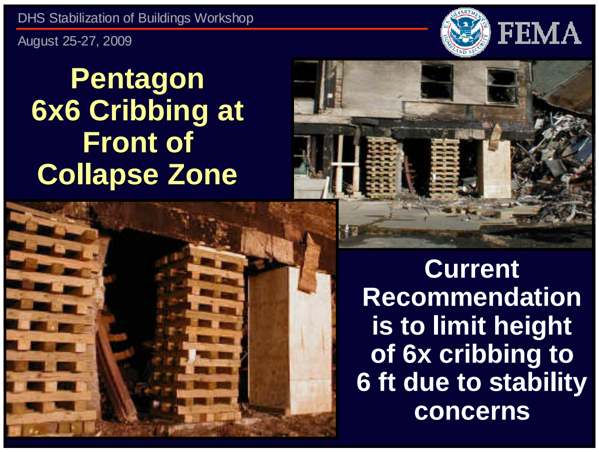
Laced Post Examples
Over 11 ft
Up to 11 ft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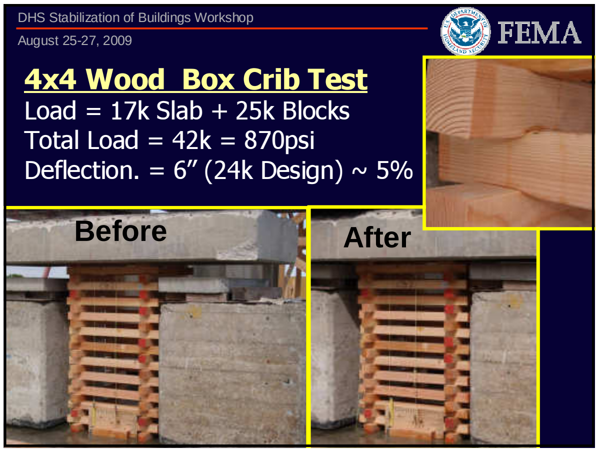
Pentagon 6x6 Cribbing at Front of Collapse Zone
Current Recommendation is to limit height of 6x cribbing to 6 ft due to stability concerns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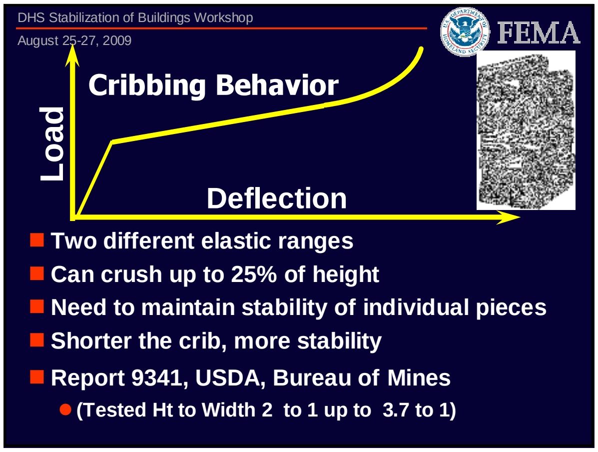
4x4 Wood Box Crib Test
Load = 17k Slab + 25k Blocks
Total Load = 42k = 870psi
Deflection. = 6" (24k Design) ~ 5%
Before
After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Cribbing Behavior
Load
Deflection
Two different elastic ranges
Can crush up to 25% of height
Need to maintain stability of individual pieces
Shorter the crib, more stability
Report 9341, USDA, Bureau of Mines
(Tested Ht to Width 2 to 1 up to 3.7 to 1)


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Typical Door & Window Shores
SS-2-1 Slide


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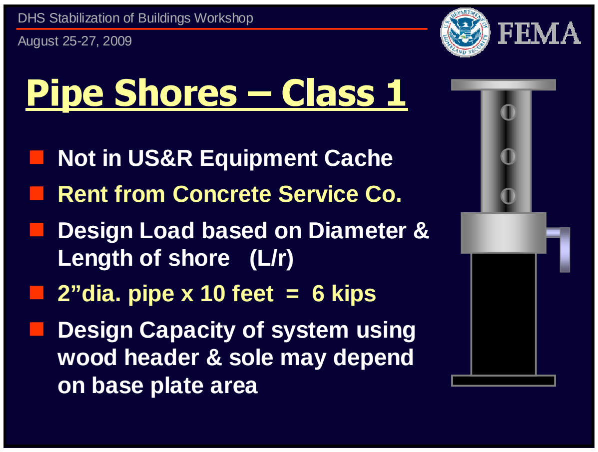
Sloped Floor/Wall Shore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Pipe Shores – Class 1
Not in US&R Equipment Cache
Rent from Concrete Service Co.
Design Load based on Diameter & Length of shore (L/r)
2"dia. pipe x 10 feet = 6 kips
Design Capacity of system using wood header & sole may depend on base plate area


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Pipe Shores - OKC - high L/D

FEMA

Aluminum Frames (Class 3)

- Available in 20k per 2 leg frame up to 50k
- Design Capacity of frame may depend on foot bearing plate
- AlumaBeams have wood nailer & can span up to 20'
  - Have been used as shelter

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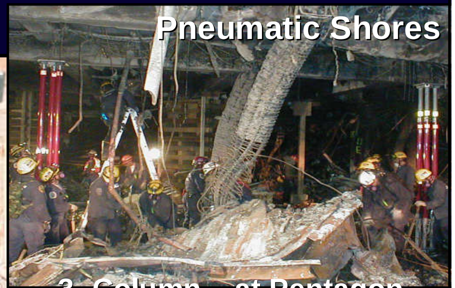
Pneumatic Shores



3- Column – at Pentagon
Spot Shores – 14ft high
Design Strength = 12K
(Design Strength, 1 - 6x6 = 14.5K)

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Paratech Rescue Strut

FEMA

Lateral Shoring Systems

- Raker Shores
- Trench & Horizontal Shores
- Tiebacks in deep excavations

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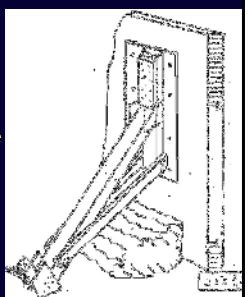
Flying Raker Shore – Spot Shore

- An initial lateral safety shore… NOT permanent !
- Must be anchored to the wall to work properly
- Use re-usable trough base instead of digging
- Use 6ft Wall Plate w/24"cleat & 60deg Raker
- Design Strength is about 1 kip.



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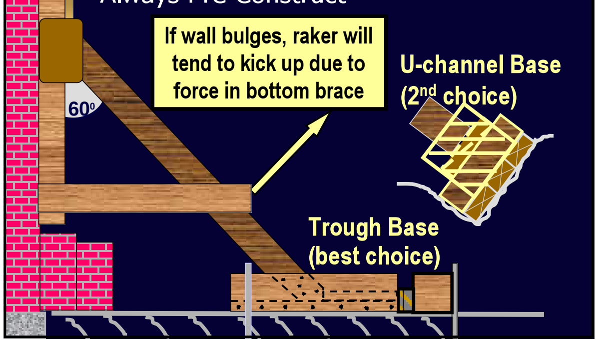
Flying Raker Shore
Always Pre-Construct

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Solid Sole Raker Shore
Used to re-support unstable or leaning walls
The Raker Shore of Choice
Class 2 as a single and Class 3 when paired
Generally erected at 45 degree angle (60 deg O.K.)
Can be utilized on Soil as well as Pavement
Pre-assemble and carry into position
Must erect minimum of two shores & tie together with x-bracing & lacing.
Design Strength is 2.5 kips each, 5 kips paired


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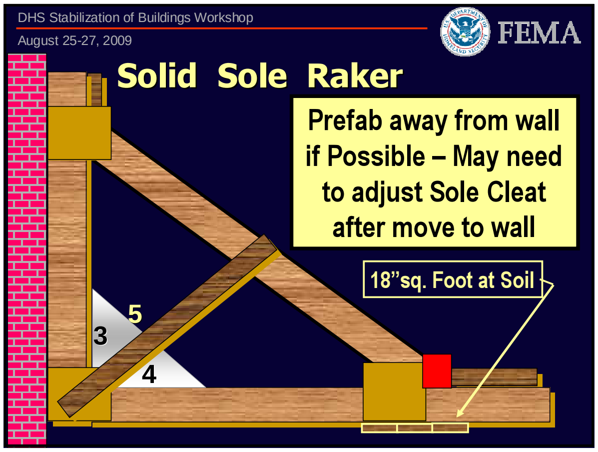
Rakers installed after Explosion
Blew out part of URM cavity wall - 1 story bldg
Needed entry here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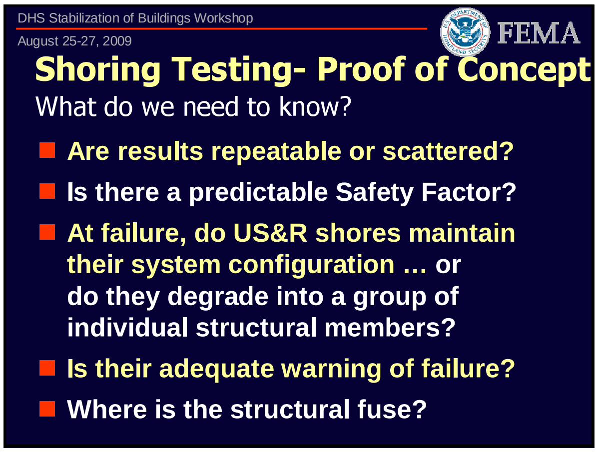
Solid Sole Raker
Prefab away from wall if Possible – May need to adjust Sole Cleat after move to wall
18"sq. Foot at Soil
5
3
4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Shoring Testing- Proof of Concept
What do we need to know?
Are results repeatable or scattered?
Is there a predictable Safety Factor?
At failure, do US&R shores maintain their system configuration … or do they degrade into a group of individual structural members?
Is their adequate warning of failure?
Where is the structural fuse?


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Vertical Shore Testing
What has been tested?
Pneumatic Struts – 2000
Performed by CA-TF3 StS
Established standards for use in US&R
Vertical Shores & Raker Systems
Wood Raker Shores & Laced Posts
Performed at DHS/FEMA StS2 Training
Proof of concept
Verified Safety Factor and Failure Mode
Demonstrated Structural Fuse


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Test Setup for Raker Shores
CATF-3
Raker
Breaker

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Raker Test Summary

- 24 Raker pairs have been tested
  - All exceeded Design Load by a factor greater than 6 (Design Load = 5k per pair)
- Properly constructed Raker System has significant reserve strength
- System performance will probably be limited by adequacy of sole plate anchorages.

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280k Vertical Load Shore Tester

US&R Training Site, Moffett Field, CA

Laced Post Plywood Laced Post

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Testing of Laced Posts

- 12 Tests performed
- Can observe significant cupping of wedges at 2x Design Load (Design Load = 32k)
  - Splitting of Headers occurs at 2x to 3x Working Load, depending on slope & direction of grain
- 4x4 - Laced Post Systems consistently resist 3 times Design Load (95k to 110k)
- Failure often occurs in posts w/knots that are near joints
- Direction of diagonal braces does not have a significant effect.
- Total deflection is about 1.5 to 2" at failure

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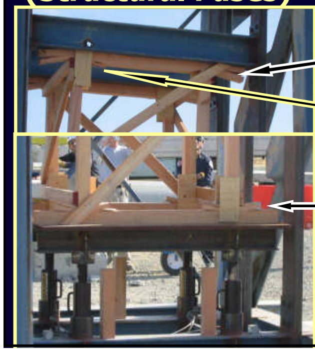
Laced Post - Signs of Overload (Structural Fuses)



Splitting of Header

Crushing of Header by Post

Cupping of Wedges

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Testing of Plywood Laced Post

4ft x 4ft Post Layout

- 6 Tests performed
- Using 24"- ¾"PlyWd strips appears to produce same results as Laced Post using 2x bracing
  - Good results with 24" strips w/ 24" clear between
  - Deflection is about same as Laced Post
  - Can achieved better results w/ closer spacing, but may be impractical (as high as 140k Load)
- Using 12"- ¾"PlyWd strips is Inadequate
  - Single Cycle Buckling occurred

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Plywood Laced Post

Prior to Loading At 115K

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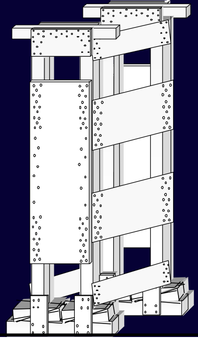
Plywood Braced Double T Tests

2ft x 4ft Post Layout



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Testing of PlyWd Braced Dbl T

- 12 Tests performed
- Need 48" to 96" – Ply on 2ft sides, but 24" ply strips OK on 4ft sides
  - Deflection is about same as Std Laced Post
  - Use 24"max clear space between ply strips on 4ft sides
  - Failure Load is at least as good as Laced Post
- Plywood may be thinner than ¾"
  - No significant change using 1/2" and 5/8"
  - Try OSB next
- Most specimen achieved over 115k Load
  - Lead to greater deflection and distortion

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The US&R Structures Specialist must:

- Imagine the original structural system
- Evaluate the remaining structural capacity
- Evaluate the structural & non-structural hazards
- Evaluate risk reducing stability improvements
- Select "best available" shoring system(s)
- Recommend shoring mitigation to stabilize the search & rescue operational area.

In the time it took to present this material to you.

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Future Shoring Testing

- Conduct additional tests using 2ft x 4ft plywood braced, 4-post shores
  - Confirm adequacy of ½" plywood
  - Confirm adequacy of 5/8" OSB
  - Confirm the minimum number of nails that are required
- Seek approval of Plywood Braced, 4-post shores in 2ft x 4ft layout

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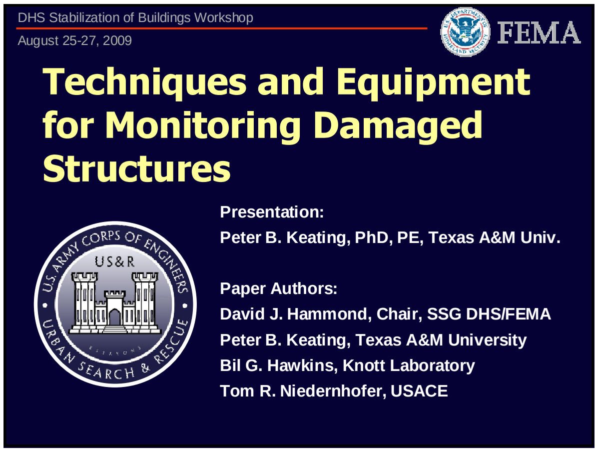
What next steps should we take?

-
-
-
-
-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Techniques and Equipment for Monitoring Damaged Structures
Presentation:
Peter B. Keating, PhD, PE, Texas A&M Univ.
Paper Authors:
David J. Hammond, Chair, SSG DHS/FEMA
Peter B. Keating, Texas A&M University
Bil G. Hawkins, Knott Laboratory
Tom R. Niedernhofer, USACE
US&R
U.S. ARMY CORPS OF ENGINEERS
URBAN SEARCH & RESCUE


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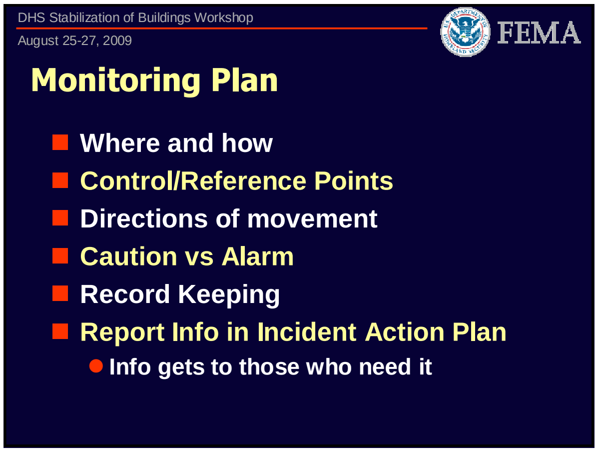
Building Monitoring
One of the methods used to mitigate risk to rescue personnel
Need to consider the Installation Risk
Elements of Monitoring
Monitoring Plan
Record Keeping
Emergency Communication Plan
Monitoring Tools
Properly Trained Personnel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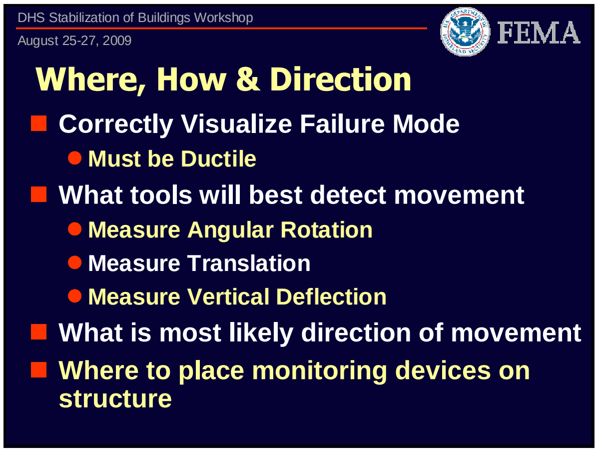
Monitoring Plan
Where and how
Control/Reference Points
Directions of movement
Caution vs Alarm
Record Keeping
Report Info in Incident Action Plan
Info gets to those who need it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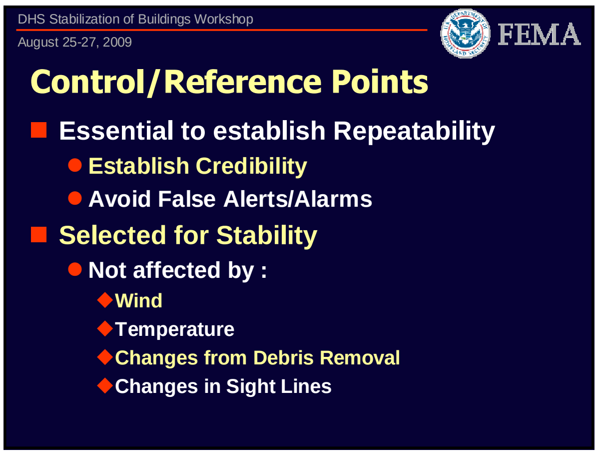
Where, How & Direction
Correctly Visualize Failure Mode
Must be Ductile
What tools will best detect movement
Measure Angular Rotation
Measure Translation
Measure Vertical Deflection
What is most likely direction of movement
Where to place monitoring devices on structure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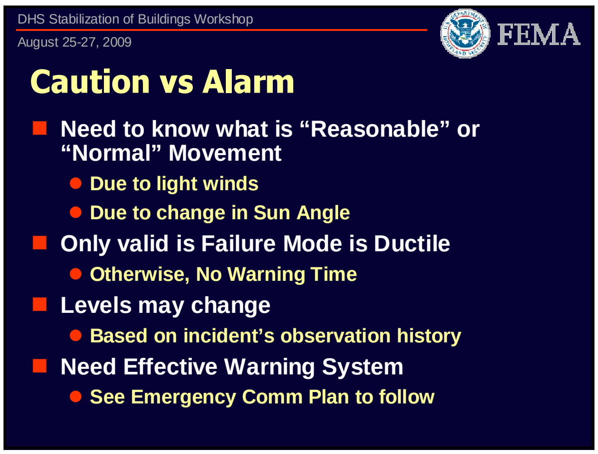
Control/Reference Points
Essential to establish Repeatability
Establish Credibility
Avoid False Alerts/Alarms
Selected for Stability
Not affected by :
Wind
Temperature
Changes from Debris Removal
Changes in Sight Lines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Caution vs Alarm
Need to know what is "Reasonable" or "Normal" Movement
Due to light winds
Due to change in Sun Angle
Only valid is Failure Mode is Ductile
Otherwise, No Warning Time
Levels may change
Based on incident's observation history
Need Effective Warning System
See Emergency Comm Plan to follow

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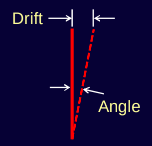
Story Drift

Compare Angle Rotation to Story Displacement – in one 12ft story



Story Drift = Lateral Displacement in 1 Story

Angle (deg)	.01	.05	.10	.15	.20	.40	.60	.80
Drift (inch)	.025	.126	.251	.337	.502	1.0	1.51	2.01

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Data Interpretation

- Most Challenging Aspect
  - No simple Rules
  - Consider overall context of Bldg & Incident
- Key Factors to Consider
  - Initial Conditions
  - Movement Magnitude & Rate
  - Movement Trend –Cyclic, Monotonic, Step
  - External Influences
- All movement must be considered "In Context"
  - OKC Murrah Bldg – "Normal" was 5/8" in 10 stories

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Reference Movements - Bldgs

- The 1, 2, 3 Rule – Normal "Noise"/ Story
  - Concrete = 1/16" (0.025 deg)
  - Steel = 2/16" (0.05 deg)
  - Wood = 3/16" (0.075 deg)
- Rough estimates only
  - Caused by change in sun angle
  - Caused by light winds
  - Day- night transition

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Reference Movements - Devices

- Plumb bob – Vulnerable to wind
- Crack Gage – Parallax may be an issue
- Smart Level – Resolution is 0.20 deg
- Laser Level – Diameter of Beam
- Total Sta/Theodolite – Depends on quality and stiffness of Tripod Set-up
- WBMS – Resolution is 0.05 deg
  - Software displays to 0.01 deg

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Record Keeping

- Written Records need to be kept of all Monitoring Devices
  - All Monitoring Devices, inc Crack Monitor
  - See next slide for suggested intervals
- Recording System can be setup and kept by IST Structure Spec Staff
  - Each TF Structure Spec should keep own Unit Log including Monitoring Data
  - Need to share data at every shift change, assuming no significant movement (Hand-off)
  - Report Info in Action Plans
    - Depends on incident & IST

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Recording Data, Intervals

- Periodically
  - Initially Hourly – Later at longer interval
  - Electronically and/or FEMA Forms
- Discussion at Shift Change
- Following Significant Events
  - Aftershocks
  - Windstorms
  - Shifting of Debris
  - Heavy Equipment – load collisions, etc

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Communication Protocols

- Need to strike a balance between Rapid Notification and Avoidance of False Alarms
  - Alert Threshold must be greater than "Normal", but less than Impending Collapse
- Must be able to Effectively Communicate any Alarm to Leadership
- A pre-determined "Alarm Level" needs to be discussed & established with Leaders so Rapid Response is Facilitated

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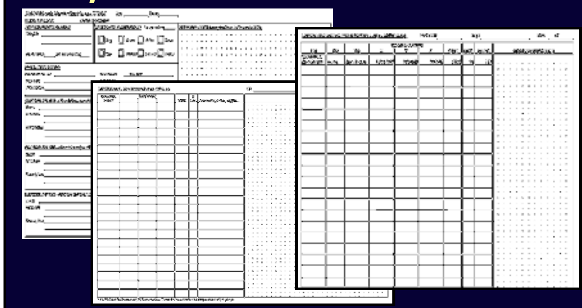
DHS/FEMA Monitor Forms



All Monitoring Forms used to hand-off information to the on-coming shifts

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Emergency Communication Plan

- Effective Warning System
  - For Caution and Alarm Warnings
- Involves Coordination
  - DHS/FEMA Task Force Leaders
  - FEMA Incident Support Team
  - Incident Command
- All must understand, and be able to Hear Warning Signals
- All must know their Evacuation Routes, and to Whom they Report

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US&R Monitoring Devices

- Total Station (Theodolite)
  - Reflectorless Total Station
- Electronic Tilt Meter (WBMS)
- Electronic Level
  - SmartLevel & SmartTool
- Laser Levels
- Plumb bob
- Crack measuring devices
- Wind Speed Measuring Devices

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Total Station

- A surveying instrument that measures both angle (horizontal & vertical) and distance
- Uses a pulse laser to measure distance to a reflectorless surface
- Can automatically convert angle and distance measurements into a pre-established X, Y, & Z coordinate system, easy to interpret movements
- Older Theodolites measured only horizontal and vertical angles, difficult to interpret.

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Total Station

- Advantages
  - Observation w/o contacting structure
  - Make Distant Observations
  - Ability to Zoom-In on Structure
  - Observe many points from One Location
- Disadvantages
  - Cost of instrument
    - 5sec Reflectorless Total Sta = $6500
  - Need Trained Operators
  - Need stable Reference/Control points
    - Difficult establishing aftershock control?
  - Can't Use w/Face Mask

Use of Total Station

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Total Station

- Potentially can be used poorly and without Reference/Control
- **False movements have been reported at several major incidents**
  - Most often as a result of someone inadvertently bumping the tripod, without having an adequate Reference/Control mark system
  - This can lead to a lack of confidence in this very important system
- **This is a very effective device that must be used properly**

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East Tower
Marginally stable

Monitor from north parking lot using Theodolite + establish link to weather service to warn of winds over 25MPH

Can't establish fall zone - would greatly limit rescue efforts

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Theodolite in North Parking Lot for East Tower
one also located East of bldg to check Wall Line E

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Witness Mark and Site Wind Gage

Vertical sight lines were run to compare with point at base of tower

Maximum movement 3/4" with 45MPH wind

Stayed relatively stable

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Wireless Building Monitor System

- Wireless Building Monitoring Sys (WBMS)
  - System uses up to 4 Sensors, placed on structure, to measure & transmit movement as an angle change.
    - Measures angle change of 0.05 degree (repeatable)
  - Signal is sent to 900mhz Spread Spectrum Receiver
    - Range is up to 1000 ft. (clear sight)
    - Not as far thru Heavy Concrete & Metal Structures
  - Receiver is linked to MS Pocket PC PDA or a Laptop by wireless, blue-tooth connection
    - PDA software polls sensors at 10 to 15 sec interval
    - PDA chirps for each coherent signal received
    - May set software to alarm for any amount of angle change
  - Available at DHS/IST, DHS/FEMA & USACE systems

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Wireless Building Monitor System

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Wireless Building Monitor System

- Advantages
  - Monitor 4 or more locations at once
  - Very accurate and can set alarm for specific amount of movement (audible & visual)
  - Portable Receiving/Alarm System
  - Remote Observation (up to 1000 ft)
  - Can Use w/Face Mask
- Disadvantages
  - High cost ($18,000 per full-system, 2005)
  - Need Qualified, Techno-Operator
  - Need planned, periodic battery recharge system
  - Need to place sensors on structure

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Electronic levels

- Electronic Levels are placed in pairs on structure to measure change in any angle (vertical or horizontal)
  - Measures angle change of 0.2 degrees
  - Cost is in $100 range, each
  - Must be continually read (no alarm)
    - New lower cost model cannot be set on zero when placed in vertical position
  - Use binoculars for remote reading
  - Must alter device to turn battery saver off

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Electronic Levels

- Advantages
  - Low cost
  - Long battery life (about 40 hours)
  - Easy to read
- Disadvantages
  - Not as accurate as WBMS
  - Need to place on structure
  - Need to place 2 in each location to measure angle change in N-S + E-W direction
  - Someone needs to read them – line of sight
  - Need to modify Battery Saver Function

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Laser Levels

- Laser Levels - placed on structure to indicate movement by changed position of the light beam on a specified target
  - May measure angle change or lateral/vertical movement
    - Accuracy depends on setup – maybe 0.2 degrees, 1/8"
    - Must be continually read (no alarm)
    - Target should be set in safe area
  - RoboToolz Laser Level
    - Low cost, but less useful
  - Hilti Laser Level - PMP-34
  - Moderate cost w/ lots of extras

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RoboToolz Laser Levels

- Cost is $100 each for tri-axial laser
- Battery life is about 14 hours (AAA batteries)
- Mount on steel angle, since device has magnets

Tri-axial

Single

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Hilti PMP-34 Laser Level

- GSA cost is $460 each for tri-axial laser
- Battery life is about 40 hours (AA batteries)
- Comes w/ case and several mounting devices
- Self leveling, and has several modes of operation
  - Single, Double, Triple, Self level off, Battery save off

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Laser Levels

- Advantages
  - Low cost
  - Easy to read
- Disadvantages
  - Not as accurate as WBMS
  - Need to place on structure
  - Need to place 2 targets for each location to measure angle change in N-S + E-W direction
  - Someone to read them – line of sight
  - Need to replace batteries
    - Every 12 hrs for RoboToolz
    - Every 40 hrs for Hilti

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Plumb Bob

- Use a Plumb Bob hung from small structure to compare to a point on the ground or pavement
  - Allows one to observe change in a leaning structure
- Advantages
  - Inexpensive, easy to use, no special skills (a rock on a string will suffice)
- Disadvantages
  - Requires one to attach to structure, constant observation, not too accurate, wind

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Crack Monitoring

- Draw or sawcut 'x' centered on crack
- Use inexpensive ($15) plastic crack monitor that can be placed across a crack

- Spray paint cracked area
- Place shims/cards in cracks
- Inexpensive, easy to read the change, but need to be checked (up close) periodically

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Monitor Wind Speed

- Low cost, hand-held devices
  - Kestrel = $100

  - Brunton = $60
- Weather Station w/ remote sensors
  - $150

Method to Monitor Disaster Site

- P vs S wave - time delay
  - P wave travels faster than S waves
  - If distance from Fault to Site is more than 50km there is opportunity to warn of Aftershocks
- Seismic Trigger deployed at Disaster Site
  - Warns when P wave arrives
  - Destructive S wave arrives later
- Pager System
  - Pagers at disaster site are signaled from sensors at fault that measure Aftershocks

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Trained Monitoring Personnel

- Need properly trained individuals
- Task Force StS may be needed elsewhere and not available for monitoring
- Monitoring help is Function of IST StS
  - Pre-scripted Mission Assignment, USACE
  - Local Land Surveyors (liability issues?)
  - Other Local Assets
- Proper Training
  - Understand US&R
  - Know what to do with observations
  - Detach from Rescue Operations

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Summary

- Monitoring requires careful planning & the reporting of reliable information
- Collapse must be proceeded by a failure mode that is slow, with measureable deformation
- Devices must be reliable and relatively simple to operate
- Monitoring must integrate into existing US&R protocol and operation

State-Of-The-Art Remote Monitoring of Buildings

Vincent P. Chiarito, P.E.
Research Structural Engineer
Vicksburg, MS
August 26, 2009

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US Army Corps of Engineers
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Definition

Remote: far removed in space, time or relation

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Some Motivation to Monitor

- Ensure function
- Identify problems
- Warning of severe problems

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Remote vs. Not Remote

- Hardwired vs. wireless
- Constantly watched or involve some help with processing data
- (“cyber infrastructure”)
- Long vs. short term; random vs. selected

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Some thoughts

- To find a forest fire, one has to see the whole forest…to find the smoke –then you know where apply action
- Same challenge with monitoring a building…
- Easy to get data these days – 20 to 30 years (and more) ago – not as easy
- Al lot of good stuff presented that covers this

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Motivation

- emphasis on what worked – early motivational example:
- Code of Hammurabi
- Deflections – observable based on loads
- Quantify what human senses perceive
  - touch
  - see
  - hear
  - smell
  - taste

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State-Of-The-Art Remote Monitoring of Buildings

Vincent P. Chiarito

Sensor Development

- Quantify what human senses perceive
  - touch – accelerometers, geophones, ae
  - see – cameras, video
  - hear - microphones
  - smell/ taste – gas detection sensors/ chemical detection

Limited spectrum - other sensors go beyond Human perception abilities

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Some History

Code of Hammurabi (2200 B.C.), King of Babylonia (taken from Construction Failure, Feld & Carper, 1997)

- If a house collapses and causes death of owner - death to builder

B. If son of owner dies - death to son of builder
…….

"…tooth for a tooth…".

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Famous "Failures"

- Leaning Tower of Pisa (Italy)
- Johnstown Flood (1889, US)
- Tacoma Narrows Bridge (1940, US)
- Malpasset Dam (1959, France)
- Hyatt Regency Hotel walkway (1981, US)

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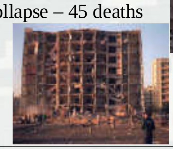
Progressive Collapse

- Oklahoma City
  - 87% in collapsed portion died (153 out of 175)
  - 5% in uncollapsed portion died (10 out of 186)

- Nairobi
  - Ufundi House collapsed – 200 deaths
  - US Embassy did not collapse – 45 deaths



- Khobar Towers
  - No collapse – 19 deaths
  - Built with British Code

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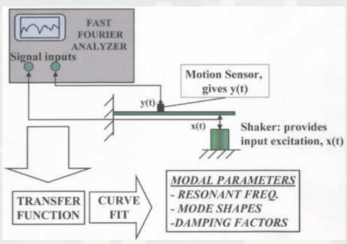
One Basic Idea of Monitoring



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5-story building

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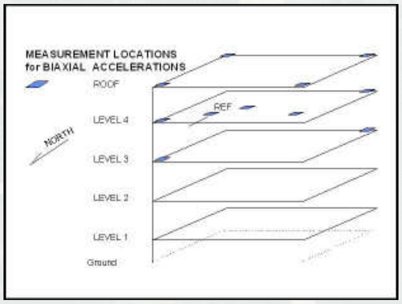
5-story building



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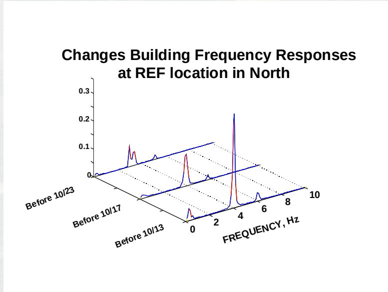
5-story building



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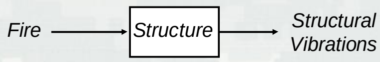
Stability Monitoring of Burning Buildings

Systems Model



Traditional Systems Theory predicts behavior based on "inputs and outputs" and the ratio of these

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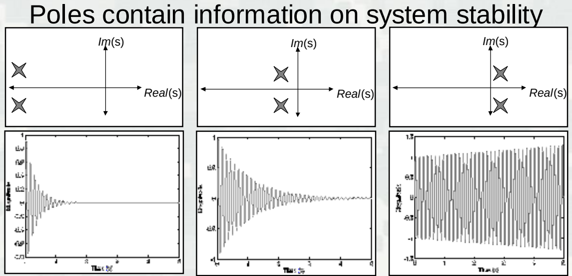
Principles of Stability Theory

Poles contain information on system stability



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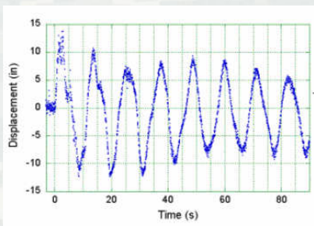
WTC Displacement Record



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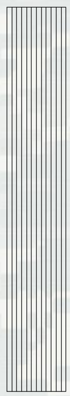
Moire Fringes



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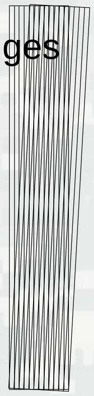
Moire Fringes



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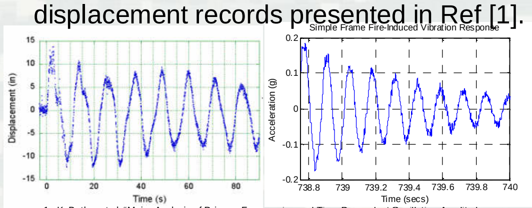
WTC 2 Displacement Record Analysis

- A Moiré analysis of video acquired from WTC 2 has resulted in a series of displacement records presented in Ref [1].



1. K. Butler, et.al, "Moire Analysis of Primary Frequencies and Time-Dependent Oscillation Amplitude Following the Aircraft Impact for WTC 2," NIST NCSTAR 1-5, Appendix K, pp.915-954.

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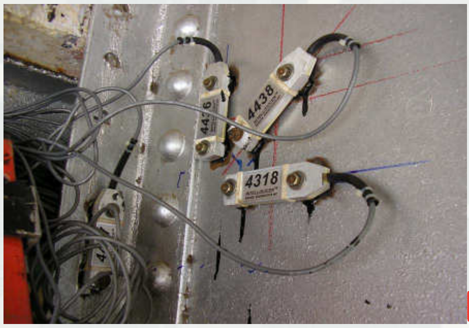
Fixed and hard wired sensors



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WBMS

Wireless Building Monitoring System (WBMS)

Exponent, in partnership with California USAR Task Force 3, has developed a system for monitoring damaged buildings and structures to improve safety in emergency response situations.

The WBMS allows emergency response personnel at an incident site to quickly assess and monitor the stability of damaged buildings and structures throughout the operation. By constantly monitoring the structure for small angular movements, it is possible to provide rescue workers advanced warning of potential collapse. Once the remote sensors are attached to the structure, the system uses precision inclinometers and digital radio technology to provide improved measurement accuracy without putting personnel in harm's way.

Key Features:

- Precision Tilt measurement in two axes
- Modular architecture, multiple sensor and receiver modules capable of monitoring several locations and structures simultaneously
- Continuous readings - more reliable than transit-based measurements.
- No false alarms from bumping transit.
- Flexible power supply options
- Adjustable alarm threshold per sensor
- Hand-held monitor with audio alert
- Hands free operation with earphone
- Flexible mounting options
- Optional Base-station

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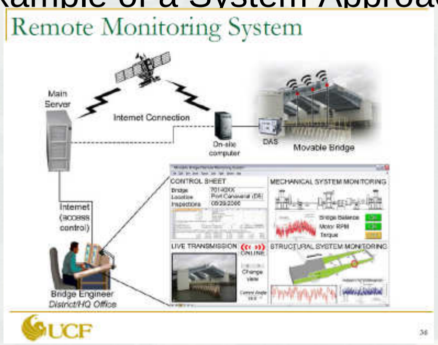
Example of a System Approach



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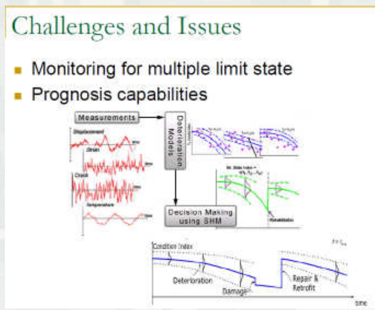

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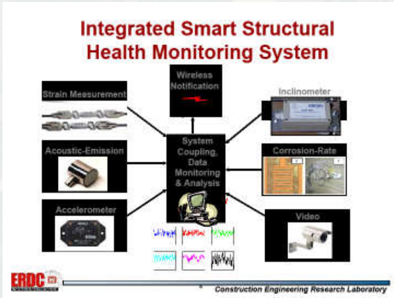
SHM on I-20 Bridge, Vicksburg



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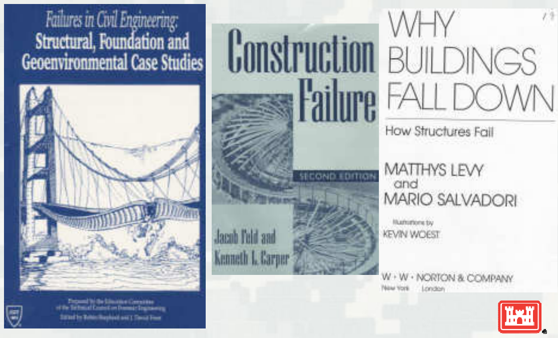
Continue to learn from History



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Some thoughts

- This workshop helps bring others together
- Others have covered the state of the art of remote monitoring – applies to more than just buildings
- Can afford to place dense arrays
- Easy to the get data; now, how to interpret, use in decision making – where we are now
- Monitoring to incorporate all different type of information: visual, movements, noises…

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Break!

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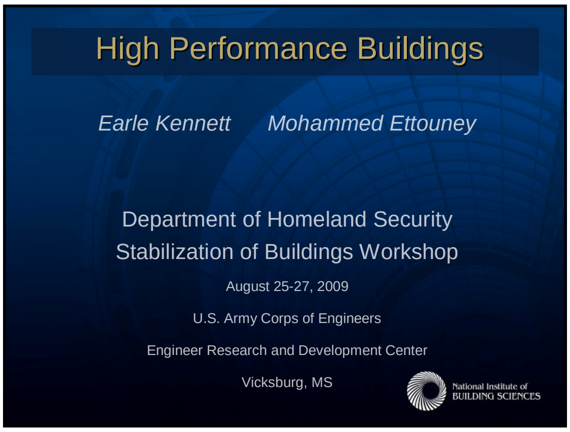
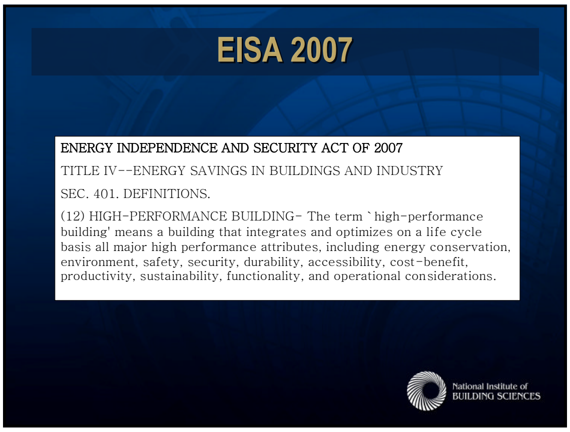
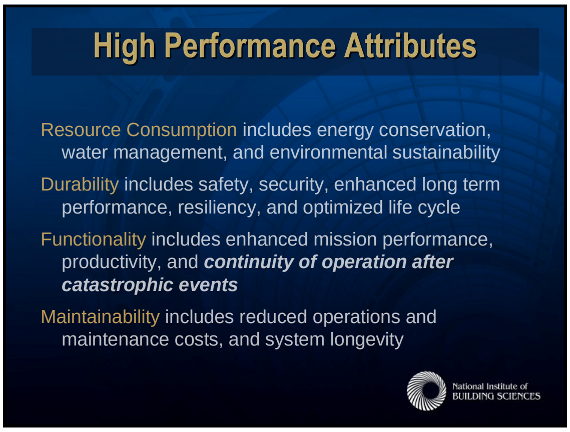
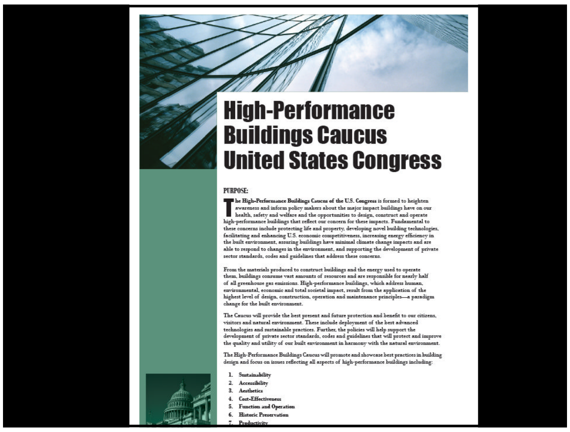
High Performance Buildings
Earle Kennett and Mohammed Ettouney









High-Performance Buildings Caucus United States Congress

PURPOSE:

The High-Performance Buildings Caucus of the U.S. Congress is formed to heighten awareness and inform policy makers about the major impact buildings have on our health, safety and welfare and the opportunities to design, construct and operate high-performance buildings that reflect our concern for these impacts. Fundamental to these concerns include protecting life and property, developing novel building technologies, facilitating and enhancing U.S. economic competitiveness, increasing energy efficiency in the built environment, assuring buildings have minimal climate change impacts and are able to respond to changes in the environment, and supporting the development of private sector standards, codes and guidelines that address these concerns.

From the materials produced to construct buildings and the energy used to operate them, buildings consume vast amounts of resources and are responsible for nearly half of all greenhouse gas emissions. High-performance buildings, which address human, environmental, economic and total societal impact, result from the application of the highest level of design, construction, operation and maintenance principles—a paradigm change for the built environment.

The Caucus will provide the best present and future protection and benefit to our citizens, visitors and natural environment. These include deployment of the best advanced technologies and sustainable practices. Further, the policies will help support the development of private sector standards, codes and guidelines that will protect and improve the quality and utility of our built environment in harmony with the natural environment.

The High-Performance Buildings Caucus will promote and showcase best practices in building design and focus on issues reflecting all aspects of high-performance buildings including:

1. Sustainability
2. Accessibility
3. Aesthetics
4. Cost-Effectiveness
5. Function and Operation
6. Historic Preservation
7. Productivity

HIGH-PERFORMANCE BUILDING CONGRESSIONAL CAUCUS COALITION
--www.HPBCCC.org--

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Breakfast Briefing on
High-Performance Buildings—Operating After Disasters

In the event of a catastrophic event, whether natural or manmade, a high-performance building needs to maintain the safety and security of its occupants while also considering the impact of the event on the mission or function of the facility and on the wider community. Owners, both public and private, must have the ability to require that their building perform to provide the capacity to remain operational after the event.

September 10, 2008 ● 9:30 am - 11:00 am
U.S. House of Representatives
2325 Rayburn House Office Building

Moderator
Henry Green, Hon. AIA, President, NIBS

Welcome Remarks
Rep. Judy Biggert (R-IL) and Rep. Russ Carnahan (D-MO)
Co-Chairs, High Performance Buildings Congressional Caucus

Determining High-Performance Security Needs
Martin Denholm, AIA, LEED AP, BSCP
Vice President, SMITHGROUP
President, Building Security Council

The Building Security Council of the American Society of Civil Engineers will provide an overview of the new ASCE Building Security Rating Program which building owners, operators and designers can use to determine their building's high performance security needs. When security is considered in a more holistic manner it will produce better, more innovative solutions which will enhance building security well beyond minimum practices.

Providing Federal High-Performance Buildings after a Disaster
Lloyd H. Siegel, FAIA
Office of Construction & Facilities Management
Department of Veterans Affairs

The VA will present their work in developing a methodology for evaluating the operational capacity of their facilities after a major disaster and developing facility design standards for providing operating capabilities after these catastrophic events.

High Performance Attributes and Stabilization of Buildings

Each of the High Performance Attributes can contribute directly or indirectly to strengthening building resiliency after an IED attack

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Energy Conservation

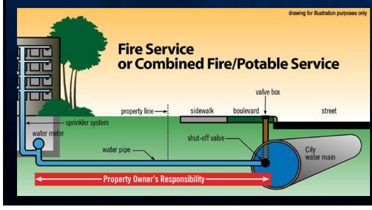
Energy Conservation Measures include

- Using advanced materials that can multifunction for both security and energy efficiency
- Using innovative building systems that can multifunction for both security and energy efficiency (double exterior walls)
- Self sustaining energy sources can provide energy during emergency conditions

Water Management

Efficient water management includes

- Water supply redundancy
- Adequate protection of pipes from natural and man-made hazards
- Adequate supply of water during emergencies



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Environmental Sustainability

Environmental Sustainability includes

- Use of new advanced materials with recycled and new composites that enhance both sustainability and blast performance.

Recent Studies Showed interrelationship Between Seismic Design and Sustainable Buildings

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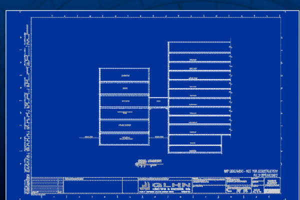
Safety

New performance codes and multi-hazard design practice can

- Provide improved resistance to multiple hazards (location of critical equipment on roof and basement)



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Security

New structural system and building envelope systems can

- Dramatically improve structural stability after a blast
- Dramatically enhance building envelope stability of both the wall system and glazing components

Enhancing Building Envelope Performance can improve safety of occupants and first responders

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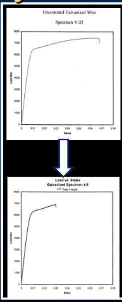
Durability

Enhanced long term material and system performance will

- Reduce structural system degradation
- High Performance Designs would ensure that such degradations are minimal



Ductility of high strength steel (such as in pre-stressed concrete buildings) is reduced as the building age

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Resiliency

Improved building resiliency can dramatically improve a community's ability to continue to function during the impending disaster.

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Life Cycle Optimization

Life cycle optimization can provide analysis for allowing increased first costs to be allocated over the entire operation of the building's life including catastrophic possibilities

- Reduce the barriers imposed by "color of money"
- Allows risk scenarios to be incorporated into the overall life cycle performance of the building.

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Maintainability

Ensure that advanced building maintenance practices that into account continued operations after catastrophic events.

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Functionality and Continuity of Operations

Providing capacity of the building to continue to function and provide mission services to support the community and disaster operations.

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Overall Goal of Continuity of Operations Attribute of High Performance Building

Continued performance of building service systems for 4 days following a catastrophic event through

- Independent systems
- Protected systems
- Redundant systems
- Flexible systems

18

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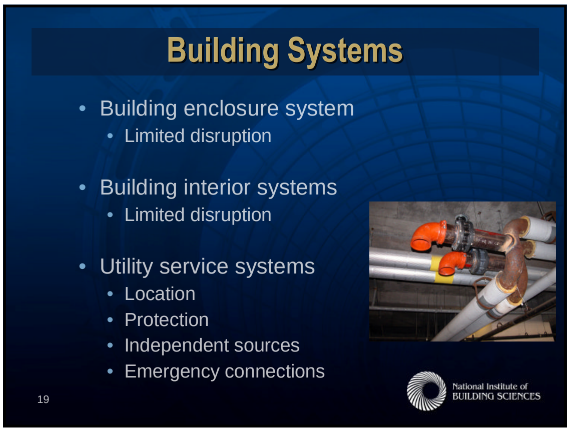
Building Systems
Building enclosure system
Limited disruption
Building interior systems
Limited disruption
Utility service systems
Location
Protection
Independent sources
Emergency connections
19
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Building Systems
Mechanical systems
Looped systems
Protected equipment
Emergency systems
Plumbing systems
Water treatment
Protected equipment
Utility storage systems
Protected storage
Ample storage
YORK
20
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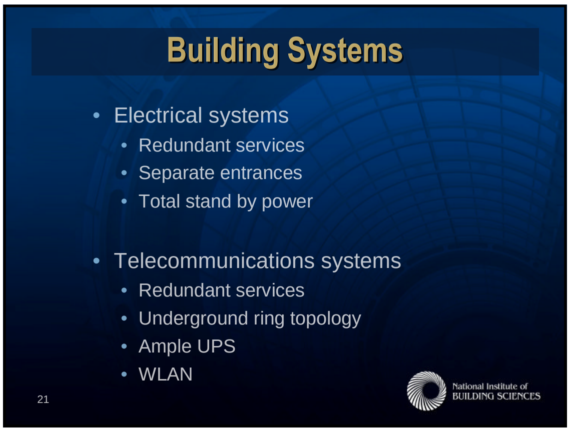
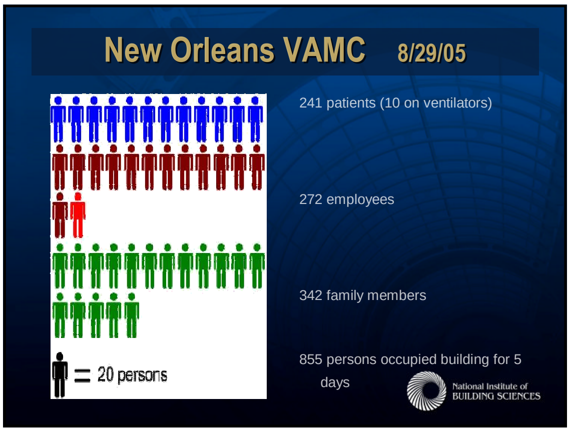
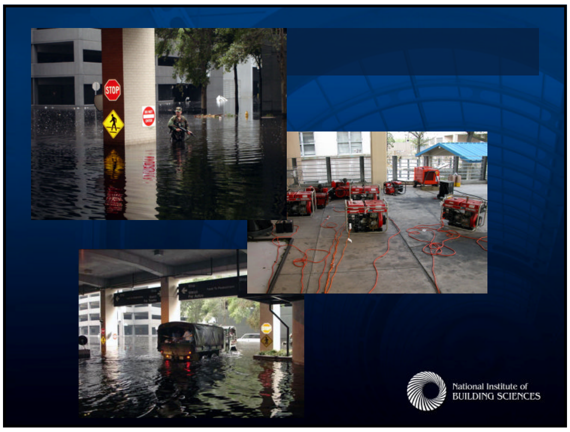
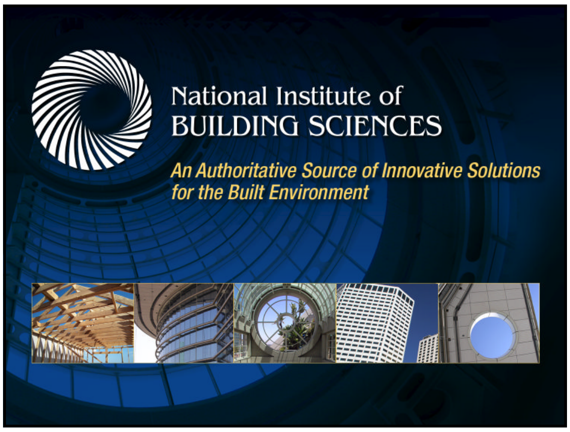

Building Systems
Electrical systems
Redundant services
Separate entrances
Total stand by power
Telecommunications systems
Redundant services
Underground ring topology
Ample UPS
WLAN
21
National Institute of BUILDING SCIENCES


New Orleans VAMC 8/29/05
241 patients (10 on ventilators)
272 employees
342 family members
855 persons occupied building for 5 days
= 20 persons
National Institute of BUILDING SCIENCES


STOP
National Institute of BUILDING SCIENCES


National Institute of BUILDING SCIENCES
An Authoritative Source of Innovative Solutions for the Built Environment

Rapidly Emplaced Composite Structural Support Systems

Toney Cummins

Rapidly Emplaced Composite Structural Support Systems

Toney Cummins
Chief, Concrete and Materials Branch
U. S. Army Engineer and Development Center
27 August 2009

US Army Corps of Engineers
BUILDING STRONG®

Background

- ERDC research in Fiber Reinforced Plastic composites materials for Force Protection reemerged in 1998.
  - Pultruded Fiberglass Structural Sections
  - FRP armor (commercial e-glass architectural)
  - Novel resin and reinforcement materials
- Rigidizable Structural Composites Program began in 2004.
- FRP materials research continues today.
  - Blast resistant membranes
  - Ultra High Performance Concrete UHPC armor cladding
  - FRP/Wood hybrids (University of Maine)

BUILDING STRONG®

Rigidizable Structural Composites Program

Problem

- Lack of high-performance Class IV structural materials and components
  - Light weight
  - Low bulk
  - Man portable
  - Tailorable
  - Multipurpose

BUILDING STRONG®

Rigidizable Structural Composites Program

Objective

To develop and evaluate a variety of composite material systems and field expedient fabrication processes suitable for producing structural composite shapes, structures and structural connections in austere environments.

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Rigidizable Structural Composites Program

Approach

Novel, cure on demand polymer resin systems will be identified and coupled with engineered reinforcement matrices to develop a suite of materials suitable for the construction of new and upgrade of existing structures.

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Rigidizable Structural Composites Program

Progress

- Innovative Resin and Reinforcement R&D
  - Collaboration with SUNREZ, Inc (BAA)
  - UV light cure elastomeric developed and evaluated
  - Moisture cure elastomeric developed and evaluated
  - LED and fiber optic resin cure initiation methods investigated
  - Cure frequency modifications using fluorescing materials
  - Reinforcement optimization for inflatable composites
  - Reinforced film optimization for inflatable structures investigated

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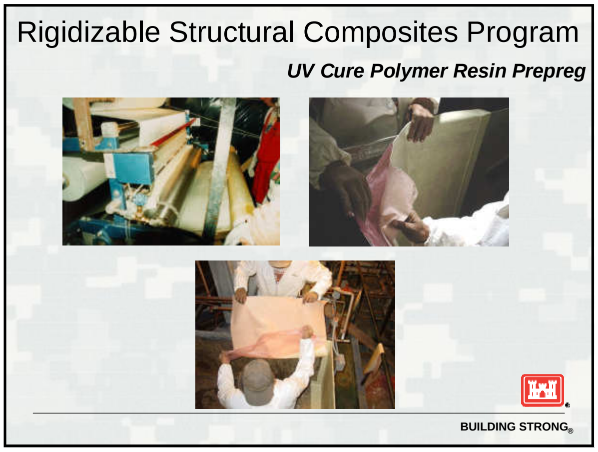
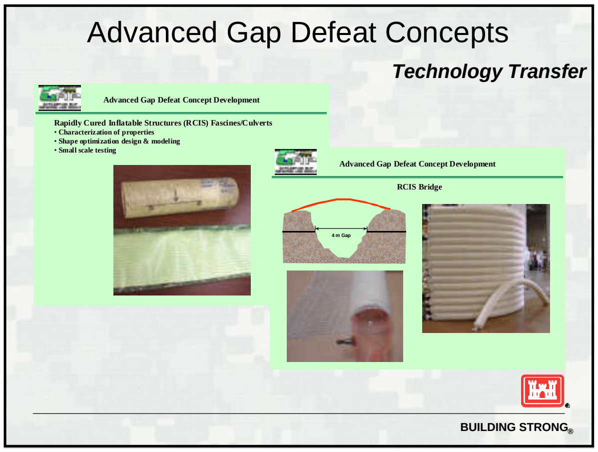
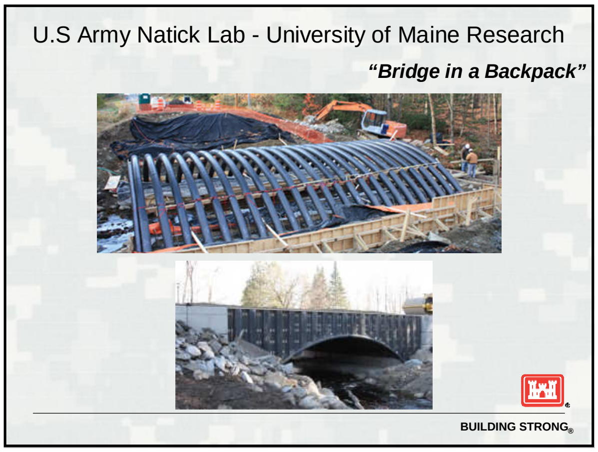
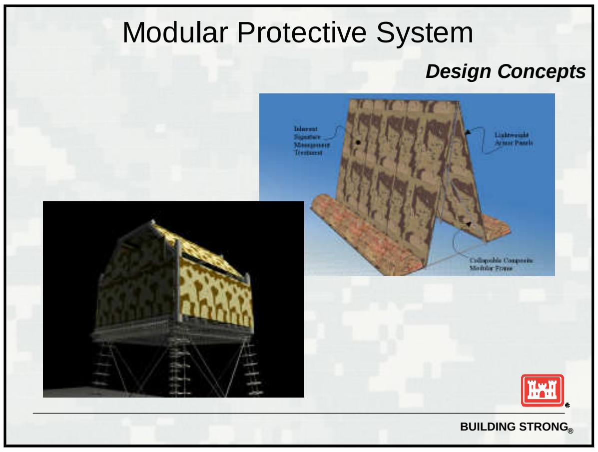

Rigidizable Structural Composites Program
UV Cure Polymer Resin Prepreg
BUILDING STRONG®


Rigidizable Structural Composites Program
Progress
▪ UV Curable Inflatable Beam
► Collaboration with SUNREZ, Inc (BAA) and Vertigo
► 2nd Generation arched beam developed and tested
► Fighting position overhead cover prototypes developed
BUILDING STRONG®

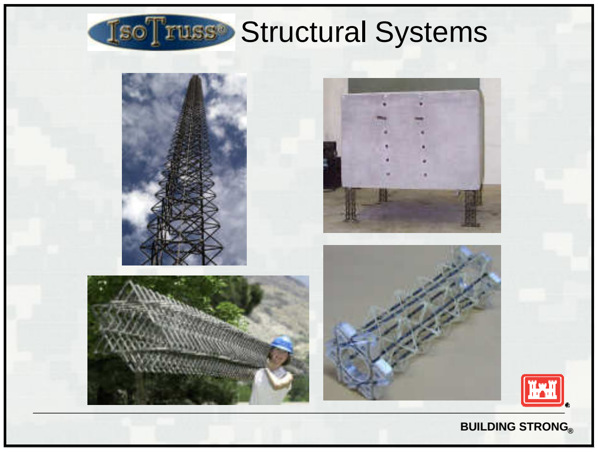

Advanced Gap Defeat Concepts
Technology Transfer
Advanced Gap Defeat Concept Development
Rapidly Cured Inflatable Structures (RCIS) Fascines/Culverts
• Characterization of properties
• Shape optimization design & modeling
• Small scale testing
Advanced Gap Defeat Concept Development
RCIS Bridge
4 m Gap
BUILDING STRONG®

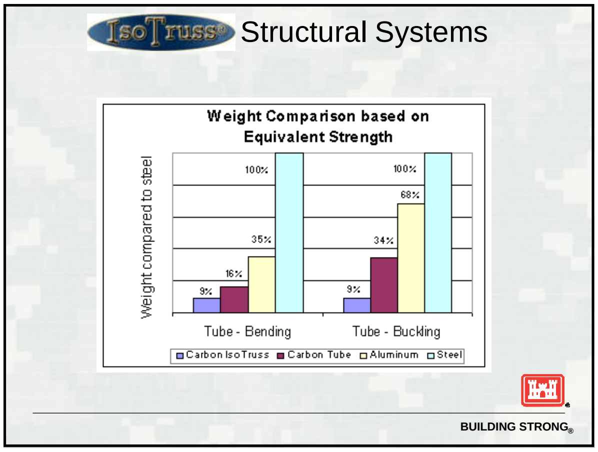

Advanced Gap Defeat Concepts
Technology Transfer
BUILDING STRONG®

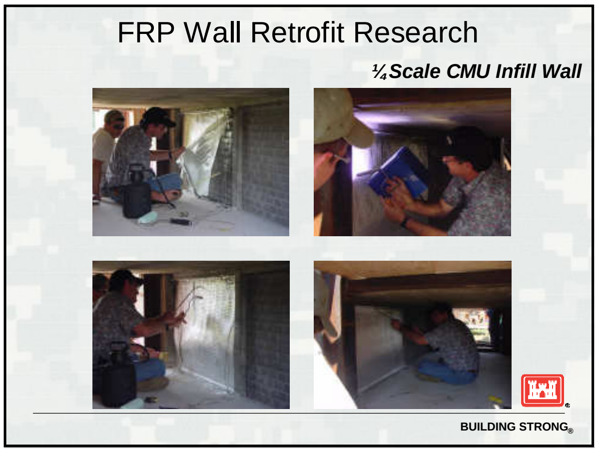

U.S Army Natick Lab - University of Maine Research
"Bridge in a Backpack"
BUILDING STRONG®

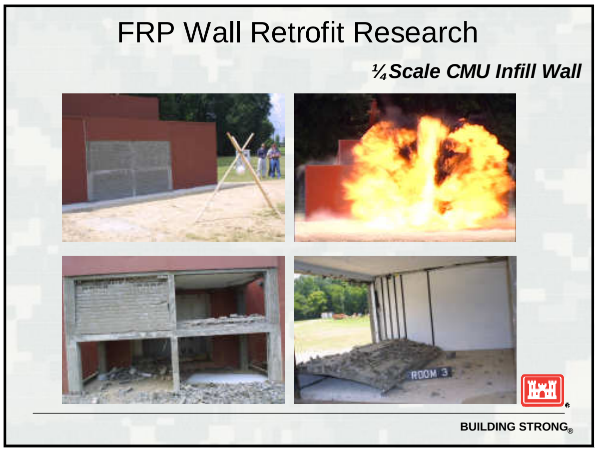

Modular Protective System
Design Concepts
BUILDING STRONG®

Rapidly Emplaced Composite Structural Support Systems
Toney Cummins

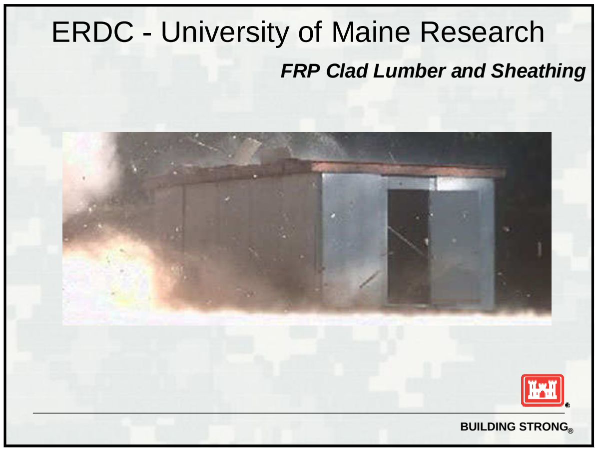






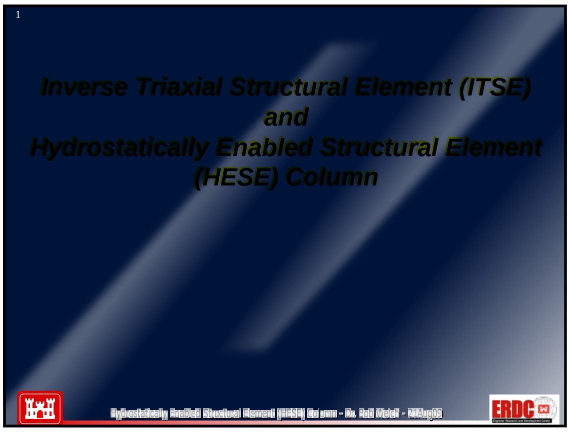


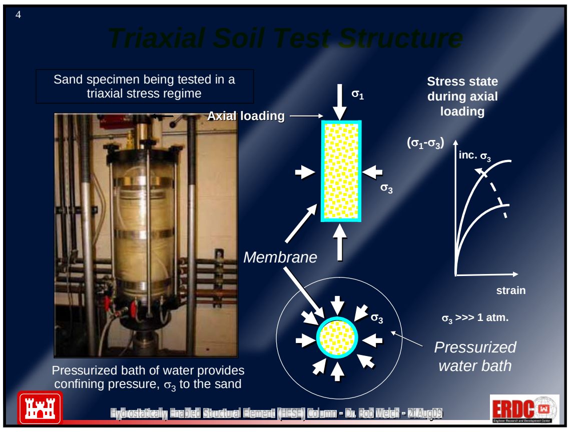
Rapidly Emplaced Composite Structural Support Systems
Toney Cummins

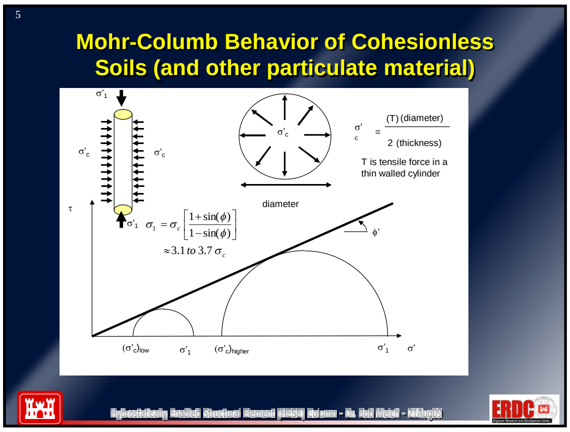


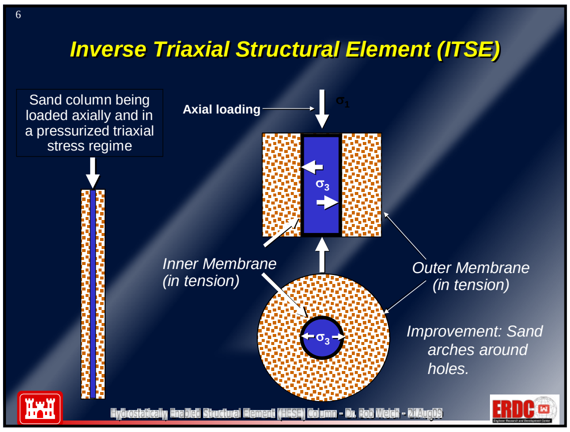
Inverse Triaxial Structural Element (ITSE) and Hydrostatically Enabled Structural Element (HESE) Column

Charles Robert Welch









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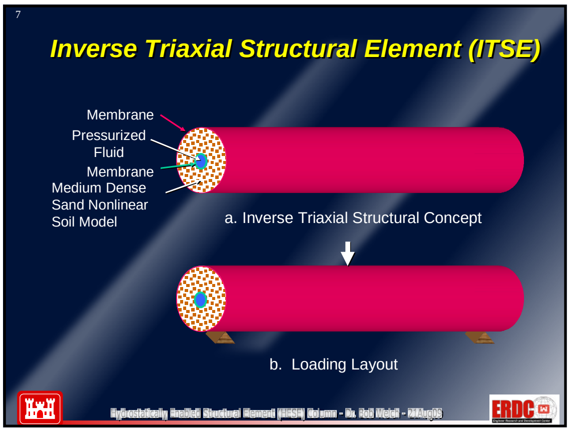

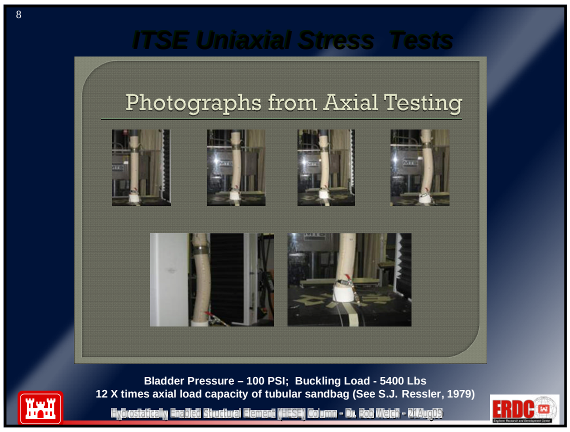

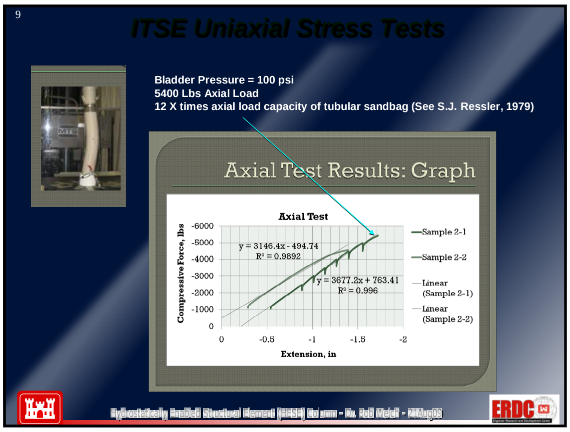

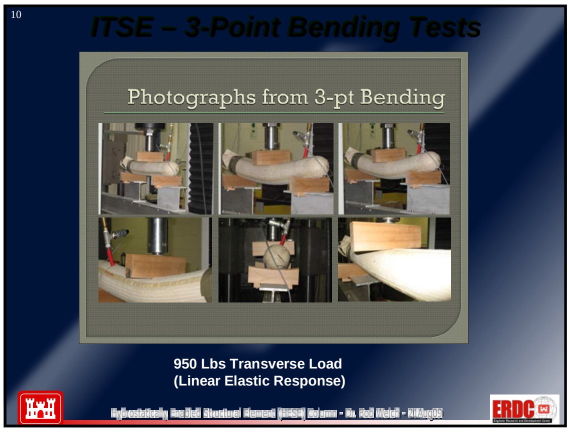

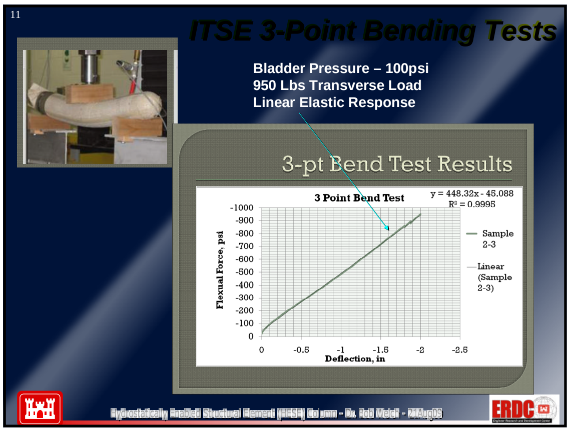

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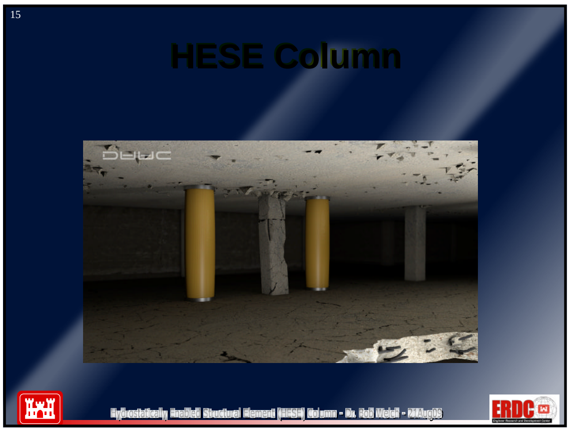

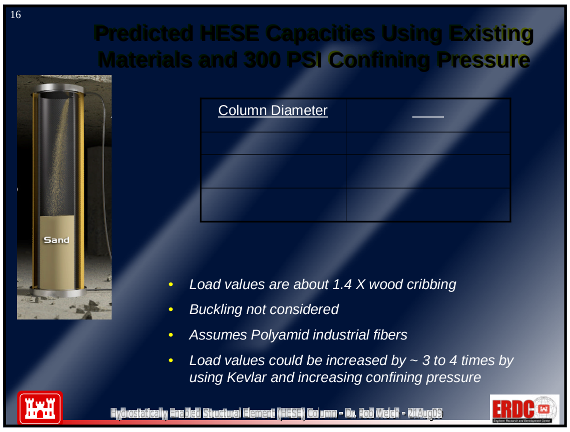

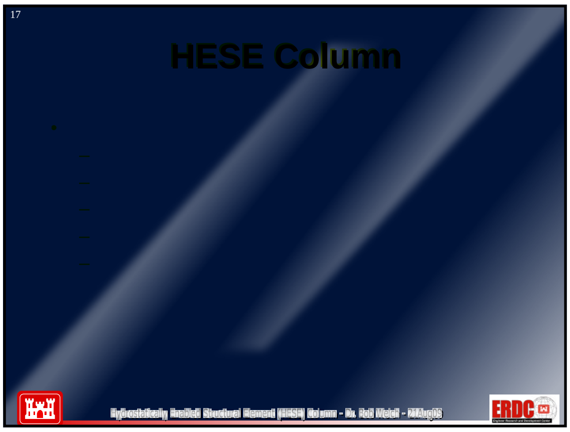

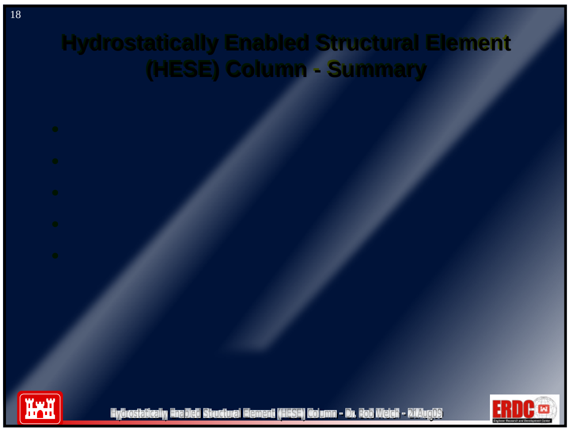

Matrices for “Stabilization of Buildings” Workshop
August 25-27, 2009, Vicksburg, MS

Lewis A. Dunn

Science Applications International Corporation

McLean, VA 22102

August 19, 2009

Breakout Sessions – Day 1 – Problems

Breakout 1A: Current Practices

Stabilization of Buildings

Day 1: Problems of Building Stabilization

Current Practices - Stabilization Challenges (post-event)	Initial response by local Fire Department	Deployment of DHS/FEMA Urban Search & Rescue Task Force	Experience-based damage assessment – identify possible voids, identify & evaluate structural hazards, failure modes, and risk mitigation means	Critical role of Structures Specialists – e.g., to identify and evaluate hazards, identify mitigation measures	Established techniques of structural stabilization and monitoring for warning of imminent collapse	Subjective risk-reward evaluations by Incident Commander, others	Other
Operate with limited time & information – and high time urgency							
Assess building collapse specifics – e.g., viable voids, live victims, hazards, type of construction, fire damage, additional loading, failure modes							
Availability of high-tech, innovative response techniques, materials, tools, systems							
Other							

What are the limitations of current practices for stabilization of buildings/urban rescue of victims?

Based on past cases (from terrorist to other abnormal events), what works well? Not as well?

Are there areas where emerging technologies/techniques could enhance current practices?

Breakout 1A: Current Practices

Stabilization of Buildings

Day 1: Problems of Building Stabilization

Key discussion points:

Current Practices - Stabilization Challenges (post-event)	Initial response by local Fire Department	Deployment of DHS/FEMA Urban Search & Rescue Task Force	Experience-based damage assessment – identify possible voids, identify & evaluate structural hazards, failure modes, and risk mitigation means	Critical role of Structures Specialists – e.g., to identify and evaluate hazards, identify mitigation measures	Established techniques of structural stabilization and monitoring for warning of imminent collapse	Subjective risk-reward evaluations by Incident Commander, Others	Other
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Assess building collapse specifics – e.g., viable voids, live victims, hazards, type of construction, fire damage, additional loading, failure modes							
Availability of high-tech, innovative response techniques, materials, tools, systems							
Other							

1) Limitations

- **Loads on shoring systems for both vertical and lateral loads**
- **Current practices are resource intensive (people and materials)**
- **Need for more information**
- **Never know how wide the safety margin is**

2) Wood shores (common construction)

- **Can limit instability and capacities are known, and the system is designed for warning**
- **Are a safety net, stable, and warn of structure shifting and loads**
- **How do you know capacity of the shores? Is there a standard way to determine what the systems of shores' behavior is?**
  - **Depends on expertise of personnel at site**
  - **Shore systems have gone through testing and applications (always improving, keeping in mind risk vs. reward)**
  - **Regarding what doesn't work well or does, there is a degree of subjectivity because demands are not known as well as the capacities and some of them work by trial and error based on experience of the user**
- **Consider time effects on stabilization**
  - **Less time, changes what type of shoring/methods to use**

3) New technology may affect first responder's response/safety

- **Sensor technology that would allow better monitoring of building's structure**
  - **Have the new technology be user-friendly in a way that it won't hinder the mission**
  - **5-10 years away from total optimal solution but examples of individual information gathering exist now— the challenge is knowing what the information says about the whole picture**
- **High-strength foam that can grow to fill up space**
- **NIST is developing new tech, short-term experimental data is there to give first responders information, in the long term the sensors will be able to tell you**
- **It would be good if tech can give us a risk profile (know if people are in inside, no need for shoring or more risk)**

4) Have built conditions of collapsed buildings

5) Better information about reward (sensing life)

<table>
<tr><th colspan="3">Based on our discussion and your experience, write in what you believe are the two most important strengths and the two most important shortcomings of current practices.</th></tr>
<tr><th>Current practices</th><th>Current Practices – Strengths</th><th>Current Practices – Shortcomings</th></tr>
<tr><td>Initial response by local Fire Department</td><td rowspan="7">1. Qualifications and training Structures Specialist personnel have

2. Properly standardized and integrated practices (multi-disciplines, medical, engineering, rescue)</td><td rowspan="7">1. Locating victims and keeping track of fire fighters and people in confined spaces

2. Skill retention and application—the skills are perishable

3. Lack of knowledge of how buildings progress to collapse after initial event. What are risks and conditions that make the building undergo the change? How do we know when it will get worse?

4. Subjectivity of practice</td></tr>
<tr><td>Deployment of DHS/FEMA Urban Search & Rescue Team</td></tr>
<tr><td>Experience-based damage assessment</td></tr>
<tr><td>Critical role of Structures Specialists</td></tr>
<tr><td>Established means of stabilization and structural monitoring for warning of imminent collapse</td></tr>
<tr><td>Subjective risk-reward evaluations by Incident Commander, others</td></tr>
<tr><td>Other</td></tr>
</table>

Breakout 1B: Stakeholders – Roles, Responsibilities, Interactions

Stabilization of Buildings

Day 1: Problems of Building Stabilization

Roles, Responsibilities, Interactions – Incident Stakeholders	Initial response and determination of priorities (if multi-structure disaster)	Assessment of disaster site – structural stability, viable voids, live victims present, structural hazards, collapse risk	Development and Implementation of Action Plans – Incident, Operational, Tactical	Implementing stabilization measures, monitoring structural stability, warning of imminent collapse	Balancing victim rescue and risk to rescuers	Coordination with public-media-families	Other
Local and State government agencies							
Federal agencies (including DHS/FEMA)							
Incident Commander							
DHS/FEMA US&R Task Force personnel, including Structures Specialists							
Building managers, operators, owners							
Live victims – and families of victims							
Others							

Who are the important stakeholders?

Are the roles and responsibilities of the different stakeholders sufficiently clear?

What lessons stand out from decision-making in past comparable disaster responses – terrorist, earthquakes, other abnormal events?

How can we improve interactions between different stakeholders?

Breakout 1B: Stakeholders – Roles, Responsibilities, Interactions

Stabilization of Buildings

Day 1: Problems of Building Stabilization

Key discussion points:

Roles, Responsibilities, Interactions – Incident Stakeholders	Initial response and determination of priorities (if multi-structure disaster)	Assessment of disaster site – structural stability, viable voids, live victims present, structural hazards, collapse risk	Development and Implementation of Action Plans – Incident, Operational, Tactical	Implementing stabilization measures, monitoring structural stability, warning of imminent collapse	Balancing victim rescue and risk to rescuers	Coordination with public-media-families	Other
Local and State government agencies							
Federal agencies (including DHS/FEMA)							
Incident Commander							
DHS/FEMA US&R Task Force personnel, including Structures Specialists							
Building managers, operators, owners							
Live victims – and families of victims							
Others							

- **Building owners are not part of the conversation**
- **Building owners and managers are not the same person; we have to treat them separately**
- **Many still need to be convinced of the threat to take future action – memories are short**
- **In the UK, owners are shown that high-performance buildings will help with continuity of business**
- **We are not yet teaching the designers of tomorrow how to design buildings for these extreme events (IEDs). What about the designers of today?**

<table>
<tr><th colspan="3">Based on our discussion and your experience, write in what you believe are the two most important strengths and the two most important shortcomings of how the stakeholders interact?</th></tr>
<tr><th>Incident Stakeholders</th><th>Interactions – Strengths</th><th>Interactions – Shortcomings</th></tr>
<tr><td>Local and State government agencies</td><td rowspan="7">1. There are some good examples in California (and other places) of first responders working well with building owners and the design community – these models can be followed or modified.

2. From a US&R standpoint, we are better prepared today than we were a few years ago for an event. We have more teams and training than before 9/11.</td><td rowspan="7">1. Tenants are reluctant to reveal vulnerabilities to extreme events to other stakeholders.

2. There are not enough engineers to be Structures Specialists:
• Not enough retraining of engineers before an abnormal event.
• Not enough preparedness and pre-training with other stakeholders.
• Structures Specialists have a high turn over rate.

3. Codes need to integrate terrorist threat mitigation and this needs to be communicated to all stakeholders.

4. Someone needs to make design-basis threat decisions to apply solid risk management principles to design.

5. The resources need to reside at the State/local level for immediate action before US&R teams arrive.</td></tr>
<tr><td>Federal agencies (including DHS/FEMA)</td></tr>
<tr><td>Incident Commander</td></tr>
<tr><td>DHS/FEMA US&R Task Force personnel , including Structures Specialists</td></tr>
<tr><td>Building managers, operators, owners</td></tr>
<tr><td>Live victims – and families of victims</td></tr>
<tr><td>Others</td></tr>
</table>

Breakout 1C: Structural Engineering State-of-the-Art-Technology Transfer

Stabilization of Buildings

Day 1: Problems of Building Stabilization

Assessment & Stabilization Technology Limitations - Stabilization Challenges (post-event)	Knowledge base on behavior of damaged/ compromised structures & components	Expedient and efficient technical-computational support tools for structural and hazard assessments	Near real-time structural health monitoring – fire, stability, risk of collapse	Decision-making tools for risk-reward assessment	Knowledge base on shoring techniques	Other?
Operate with limited time & information – and high time urgency						
Assess building collapse specifics – e.g., viable voids, live victims, hazards, type of construction, fire damage, additional loading, failure modes						
Availability of high-tech, innovative response techniques, materials, tools, systems						
Other						

Given the special needs of building stabilization (e.g., high time urgency but need for accurate decision-making), what are the gaps and limitations of today's state-of-the-art structural engineering in this area?

Do we need better approaches to simplify complex structural engineering concepts for utilization by non-structural engineers?

What can be learned from multi-hazards (e.g., earthquakes, wind) in improving structural engineering responses?

Where does technology transfer need improvement?

Breakout 1C: Structural Engineering State-of-the-Art-Technology Transfer

Stabilization of Buildings

Day 1: Problems of Building Stabilization

Key discussion points:

<table>
<tr><th>Assessment & Stabilization Technology Limitations - Stabilization Challenges (post-event)</th><th>Knowledge base on behavior of damaged/ compromised structures & components</th><th>Expedient and efficient technical-computational support tools for structural and hazard assessments</th><th>Near real-time structural health monitoring – fire, stability, risk of collapse</th><th>Decision-making tools for risk-reward assessment</th><th>Knowledge base on shoring techniques</th><th>Other</th></tr>
<tr><td>Operate with limited time & information – and high time urgency</td><td colspan="6" rowspan="4">State-of-the-art – Needed Research

• Knowledge base on behavior of damaged structures is limited. Research is needed to investigate and understand the load capacity of damaged structural systems and elements, including connections.

• FOG is the state-of-the-art for local assessments. The information is primarily based on seismic events. More case examples and data are needed from blast events (international).

• There is a need to set up a command center operation that would bring in structural experts to monitor video feeds from first responders to provide engineering advice and technical expertise until structural engineers arrived on site (usually 12 hours).

• Explore the possibility of providing major Fire Department safety officers StS-related training to assist in assessing blast-related damage after an event and before the arrival of structural engineers.

• The state-of-the-art for real-time monitoring systems is robust and growing.

• There was limited time, so the group did not get into advanced technologies and opportunities.</td></tr>
<tr><td>Assess building collapse specifics – e.g., viable voids, live victims, hazards, type of construction, fire damage, additional loading, failure modes</td></tr>
<tr><td>Availability of high-tech, innovative response techniques, materials, tools, systems</td></tr>
<tr><td>Other</td></tr>
</table>

Breakout Sessions – Day 2 – Solutions

Breakout 2A: Analytical Monitoring and Assessment of Near-Collapse Buildings

Stabilization of Buildings

Day 2: Solutions

Assessment & Stabilization Methods - Stabilization Challenges (post-event)	Current Practices		Possible Innovations			
	Experience-based/subjective evaluation of situation, identification of mitigation actions, development of operational plans	Established stabilization techniques – e.g., monitoring, shoring	Advanced assessment support tools/systems – post disaster structural assessments	Advanced real-time monitoring/ assessment technologies/ systems	Advanced stabilization techniques/ materials	Other
Operate with limited time & information – and high time urgency						
Assess building collapse specifics – e.g., viable voids, live victims, hazards, type of construction, fire damage, additional loading, failure modes						
Availability of high-tech, innovative response techniques, materials, tools, systems						
Other						

What innovative *analytic* practices/techniques/systems (both structural and non-structural) should be pursued to enhance assessment, stabilization, and monitoring of near-collapse buildings? To lessen risk to rescuers?

Are there differences between immediate and long-term stabilization analytical techniques?

How important are onsite and offsite technologies?

How mature are the needed technologies?

Breakout 2A: Analytical Monitoring and Assessment of Near-Collapse Buildings

Stabilization of Buildings

Day 2: Solutions

Key discussion points:

<table>
<tr><th rowspan="2">Assessment & Stabilization Methods - Stabilization Challenges (post-event)</th><th colspan="2">Current Practices</th><th colspan="4">Possible Innovations</th></tr>
<tr><th>Experience-based/subjective evaluation of situation, identification of mitigation actions, development of operational plans</th><th>Established stabilization techniques – e.g., monitoring, shoring</th><th>Advanced assessment support tools/systems – post disaster structural assessments</th><th>Advanced real-time monitoring/ assessment technologies/ systems</th><th>Advanced stabilization techniques/ materials</th><th>Other</th></tr>
<tr><td>Operate with limited time & information – and high time urgency</td><td colspan="6" rowspan="4">
Current Practices

Hybrid methodology that relies on previous computational models coupled with sensor data
Laser scanner in the UK—downside is it is expensive, upside is it takes 10 seconds and measures to the millimeter
Multi-mapping 3-dimensional laser imaging (360 degrees)—covers dead spots
Imaging tool to look through structure (laser system is part of the broader part) both on surface and through the structure with wide range of frequencies
Reach-back technologies exist (needs to be refined)

Possible/Needed Innovations

Something to run modeling and sensing at the same time, create real-time analytical models on site
Assessing what is critical, feedback from damage viewed
Real-time laser modeling and having software that picks up changes in structure
GPS technology to detect shifts in building structures to predict structural collapse
Map to monitor displacements—remote way to monitor vibrations (frequency of interest)
Sonar technology to detect structural failure
Figure out column curve so first responders can determine how the geometrical structure will work
Effective way to make simplified idealized model to assess strength and stability of supporting columns by means of column curve and interactions
Short-term focus on simplified analysis that would be on the order of a 1-day turnaround for first responders
Finding out what will save more first responders lives by detecting imminent collapse
Something less resource-intensive like deployable resins glue and foams to help stabilize buildings
Simple modeling tool that can be comparable to complex models
Offsite technologies to analyze buildings
Offsite service will be very important in supporting the effectiveness of onsite services
Today, no real offsite monitoring, but a potential problem is another layer of communication failure
24=hour computational station that can build models with quick turnaround
Onsite monitoring

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Breakout 2A: Analytical Monitoring and Assessment of Near-Collapse Buildings

Stabilization of Buildings

Day 2: Solutions

<table>
<tr><th colspan="3">Based on our discussion and your experience, what are the two most important analytic innovations that should be pursued for assessment & stabilization of buildings near collapse? Short term? Longer term?</th></tr>
<tr><th>Stabilization Challenges (post-event)</th><th>Short-term “Top Priority” (1-3 years)</th><th>Longer-term “Top Priority” (4-7 years)</th></tr>
<tr><td>Operate with limited time & information – and high time urgency</td><td rowspan="4">1. Need to know how to identify the local damages in order to have local effects to identify, monitor, and repair.
2. Need standardization of data collection: (e.g., MRI). Helps with onsite and offsite communication (one way to collect history: represent by either power spectral density or autocorrelation spectral density).
3. Need multisensory system with capability to fuse useful portion of information.
4. Need to create simplified models to predict collapse.
5. Need to be able to predict what will come next, moment to moment (e.g.,offsite sees satellite/maps of buildings and calculates within time to save lives).</td><td rowspan="4">1. Need to identify critical failure modes that will guide what sensors are appropriate and what analytical tools are capable of capturing those failure modes.
2. Need to broaden view of building types, better categorization of building types for modes of failure.
3. Need to identify role of non-structural components and the effects of rubble piles on structures. Need to quantify elements that were not meant to be structural (potential frames problem).</td></tr>
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Breakout 2B: Experimental Strategies for Examining Near-Collapse Buildings

Stabilization of Buildings

Day 2: Solutions

<table>
<tr><th rowspan="2">Monitoring Decisions & Techniques - Monitoring Requirements</th><th colspan="2">Current Practices</th><th colspan="5">Possible Technology/Tools Innovations</th></tr>
<tr><th>Initial assessment of monitoring requirements & development of overall monitoring plan</th><th>Reliance on established monitoring tools, techniques, operating procedures</th><th>Advanced monitoring techniques/ systems – e.g., wireless sensor network-computer systems</th><th>Designed-in Structural Health Monitoring systems</th><th>Remote sensing: Laser, thermography, ultrasonic, etc.</th><th>Knowledge database of simulated failure scenarios</th><th>Other</th></tr>
<tr><td>Warning of structural movement in failure mode of concern</td><td colspan="7" rowspan="6">What are the most promising experimental innovative techniques that should be pursued for monitoring of buildings near collapse?

How important is portable equipment? How light?

What difficulties would need to be overcome to develop such techniques?

Is there potential multifunctional equipment -- usable in more than one field?

What fields, e.g., bridge inspection and building stabilization?</td></tr>
<tr><td>Warning of debris or other localized movement</td></tr>
<tr><td>Provide warning of shoring stabilization loss</td></tr>
<tr><td>Adaptable to specific building near-collapse situation</td></tr>
<tr><td>Permit distinguishing benign from non-benign structural movement</td></tr>
<tr><td>Acceptable cost and false alarm risk</td></tr>
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Breakout 2B: Experimental Strategies for Examining Near-Collapse Buildings

Stabilization of Buildings

Day 2: Solutions

Key discussion points:

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Need to define what type of data is critical for monitoring of buildings before we focus on specific types of sensors and systems. The data collected must be relevant and useable.
Things to monitor: Fire, Structural Systems, Envelope, Directional
Types: pre-positioned systems/systems carried by first responders
Buckling of columns (e.g., WTC-1993 and OKC)
Can this be seen/monitored? (change in frequency? – ping with laser/sound beam)
Initial assessments – what tools do we need/what do we have?

Define the questions
Can now monitor ductile failures, not brittle failures
Definition of sensor types, interpretation, how disseminate to stakeholders
Rapid visual screening
Timing of failure?
Know what we are protecting (victims, rescuers, existing critical infrastructure, other things under jurisdiction of DHS)

Two-pronged approach

Pre-monitoring
Monitoring carried out by responders

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Breakout 2B: Experimental Strategies for Examining Near-Collapse Buildings	Stabilization of Buildings	Day 2: Solutions

Stabilization of Buildings

Based on our discussion and your experience, what are the two most important ***experimental*** innovations that should be pursued to enhance capabilities for monitoring of buildings near collapse? Short term? Longer term?

Monitoring Requirements	Short-term "Top Priority" (1-3 years)	Longer-term "Top Priority" (4-7 years)
Warning of structural movement in failure mode of concern Warning of debris or other localized movement Provide warning of shoring stabilization loss Adaptable to specific building near-collapse situation Permit distinguishing benign from non-benign structural movement Acceptable cost and false alarm risk	1. Define what we want to collect 2. Define what is critical for risk assessment – tailor for specific building types 3. Wireless systems that consider the countermeasures to secondary IEDs (i.e., jammers) 4. Wireless standard for communications 5. Portable power 6. Cost-effective systems that can be widely deployed	1. Design and adapt monitoring equipment 2. Enhance user/stakeholder interface (interpretation and dissemination of data)

Breakout 2C: Decision-Making

Stabilization of Buildings

Day 2: Solutions

Decision-making Challenges – / Decision-Makers	Initial assessment – including type of construction, existence of viable voids and live victims, hazards, fire damage, failure modes	Determining priorities – particularly for incident with many structures, with destructive role of non-structural components	Developing Action Plans – including approaches to hazard mitigation	Securing structure, removing surviving victims	Balancing victim rescue and risk to rescuers	Handling bystanders, families of victims, media	Assessing resources needs	Other
Local-State-Federal Government								
Incident Commander								
Task Force Leader								
Structures Specialists								
Building owners-managers (private)								
Other								

Are there innovative approaches, techniques, or systems that would facilitate or strengthen effective and timely decision-making in urban search and rescue/stabilization of buildings situations?

Are there real-time prioritization techniques that are suited for this problem?

Can existing prioritization methods from other areas be used efficiently here?

More broadly, are there techniques to strengthen interaction among stakeholders?

Breakout 2C: Decision-Making

Stabilization of Buildings

Day 2: Solutions

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<td>Local-State-Federal Government</td>
<td colspan="8" rowspan="6">
• Decision-making is the toughest aspect of US&R.
• Monitoring techniques and tools are available to aid in decision-making, but more effective/efficient tools are needed.
• Train more local StS to have faster assistance because of the time it takes for US&R to arrive.
• Train engineers on effects of fire. Fire protection engineering knowledge is limited.
• Red/yellow/green card event works for earthquakes, but is not enough training for a blast/potential collapse. However, trained engineers are better than no engineers.
    • Engineers can be too conservative in assessment.
    • False alarms reduce credibility.
• NYC has on-call engineering contracts for emergencies.
• DHS could support the creation of State “retainer” engineers to cover local response.
    • Local gov’t officials and building owners need to understand system and be prepared.
• Have to develop relationship with fire departments—have engineers train firefighters.
• Immediate (electronic) availability of building drawings would aid in rescue decisions.
• Need more data collection techniques.
• Need better understanding of how to interpret data.
• Need better rules of thumb based on new data and information.
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Breakout Sessions – Day 3 – The Future

Breakout 3A: High-Performance Building Design

Stabilization of Buildings

Day 3: Future Initiatives

Whole Building Design – Requirements for Improved Stabilization	Improved knowledge database on structural responses and failure modes – to enhance future building design	Innovative design approaches, e.g., performance-based engineering	Built-in advanced wireless monitoring sensors/systems for real-time automated structural assessment	Use of advanced techniques/ materials	Building envelope modifications	Enhanced non-structural components	Other
Mitigate structural impacts of abnormal events – terrorist, earthquake, other							
Lessen risk of progressive collapse – or extend time prior to such collapse							
Facilitate post-event assessment – structural health, existence of multi-hazards							
Increase likelihood of viable voids after abnormal events – and means of detecting voids							
Facilitate detection and rescue of living victims							
Other							

What requirements would need to be addressed as part of a "high-performance building design" approach to improve building stabilization after an abnormal event?

How would building design practices be modified?

Where are there opportunities for technology innovation?

Are there opportunities for DHS to interact with other entities to explore whole building design?

Breakout 3B: Innovative Systems and Equipment

Stabilization of Buildings

Day 3: Future Initiatives

Technology Innovations-Stabilization Challenges (post-event)	Advanced tools/systems for real-time assessments of building structural damage, failure modes, risk of progressive failure	Advanced/ more robust wireless monitoring & warning technologies/ systems – fire, structural health-integrity, victims	Advanced techniques/ materials for building stabilization	Risk-reward decision support systems	Readily accessible knowledge data base – structure behavior, fire impact, shoring and other field-simulation tests	New technology transfer/ training innovations	Other
Operate with limited time & information – and high time urgency							
Assess building collapse specifics – e.g., viable voids, live victims, hazards, type of construction, fire damage, additional loading, failure modes							
Availability of high-tech, innovative response techniques, materials, tools, systems							
Other							

What requirements would need to be addressed as part of a "high-performance building design" approach to improve building stabilization after an abnormal event?

What innovative systems and equipment should be pursued to enhance future capabilities for stabilization of buildings in urban search and rescue operations?

Breakout 3C: Advanced Materials	Stabilization of Buildings	Day 3: Future Initiatives

Advanced Materials Opportunities – Stabilization Challenges	Whole Building Design for improved building stabilization	Use of advanced materials for critical structural components	Retrofitting buildings with advanced materials for blast protection	Hardening sensors/ networks in wireless, remote structural health assessment systems	Advanced shoring materials	Other
Operate with limited time & information – and high time urgency						
Assess building collapse specifics – e.g., viable voids, live victims, hazards, type of construction, fire damage, additional loading, failure modes						
Availability of high-tech, innovative response techniques, materials, tools, systems						
Other						

What are the most promising opportunities to make use of advanced materials to improve building stabilization – pre-event or after an event?

Breakout 3 All

Stabilization of Buildings

Day 3: Future Initiatives

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<td>Operate with limited time & information – and high time urgency</td>
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• Take into account what happens if abnormal situation arises and the building is a partially damaged system.
• Take all parts of industry from owners to first responders when using new materials.
• Standardize design criteria.
• “Life Cycle” would take into account abnormal loads, partial damage, if from day one a balance between retrofits is taken into account. What is “Life Cycle” and how to implement? (Costs, benefits, lifespan)
• Most challenging part of lifecycle: lifespan. Monitoring data over period of time needed to properly model for lifecycle.
• Building code—minimum requirement for safety: who is making investment (have owner buy in to changes) technology should not increase investment costs.
• Standardize guidance for engineers on what the risks are and educate the public (e.g., sustainability movement).
• Emphasize more on practitioner education on current methodology and knowledge base. Lowest price should not be key factor, design should be.
• Opportunity for R&D to protect first responders themselves.
• Streamline real-time information to first responders (decision-makers) of building’s health.
• Standardize format of electronic/paper forms (e.g., Microfilm vs CDs).
• Technology to bridge gap between first alert to entering building with regards to risk. Help first responders assess whether or not to go in.
• Obtain more information via scanners to know more about event in order to put into guidelines to help in first critical hours.
• Protect against potential second wave attacks.
• Database should be easily accessed by decision-makers in real-time.
• Potential solutions should come out of database based on past events.
• Pay close attention to the classification of database and who has access.
• Education component needed to let public/industry know how the materials are used/what they are.
• Standardize use/application of advanced material application, have test procedures set.
• Know more about what kind of hazard affects mode of failure and in what way (manual).
• Advanced Material Database will include not just existing materials but new materials that will have to be tested in a standardized way.
• New materials should increase margin for safety and not just lower costs or strengthen materials for the sake of making them better.
• Investments should look at many aspects not just single aspect.
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