

Structures Subjected to Blast Loading: Protection, Stabilization and Repair

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To rise up 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 US Army Engineering Research and Development Center), industrial partners and several universities. One of the group's current research projects focuses on using nanostructural 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 nano particle), 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 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.

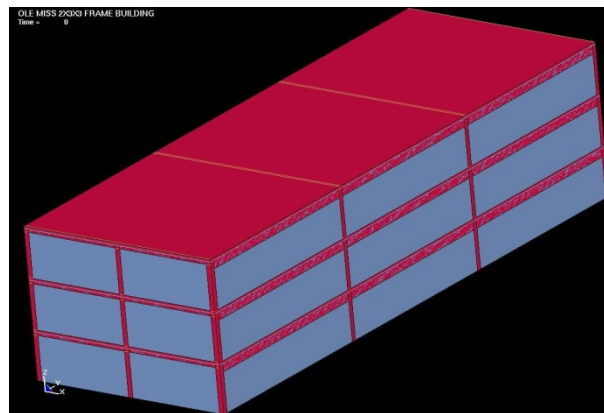
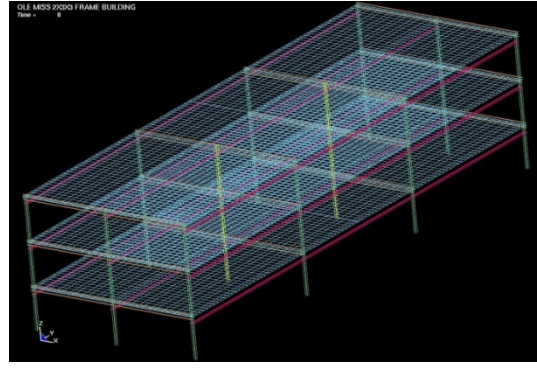
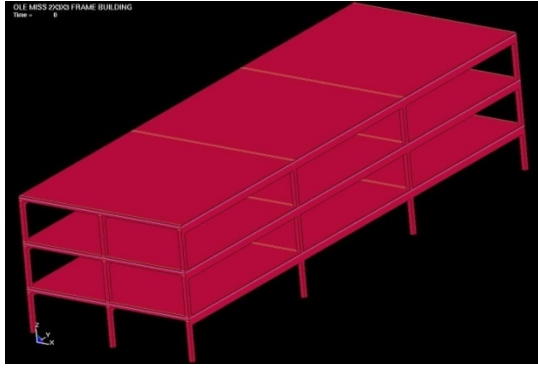


Figure 1 Representative RC MRF critical facility including curtain walls

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.



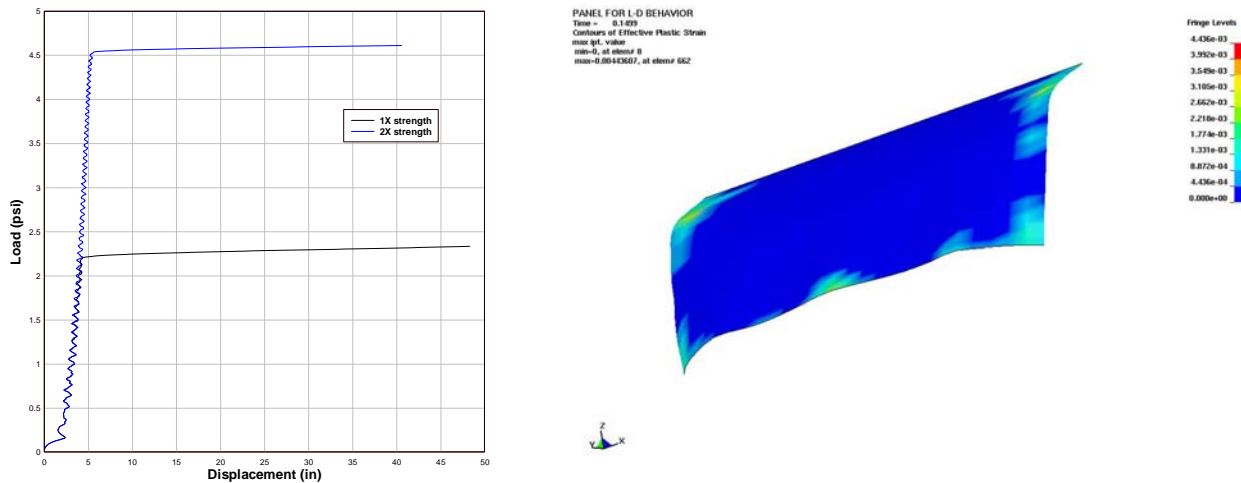
a. Concrete frame and slab subsystem (~300,000 solid elements) b. Steel reinforcement elements (~56,000 beam elements)

Figure 2 Finite Element Model Details

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.



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. Example of results of the eccentric side blast scenario are shown in Figure 4 for the three blast charge weights.

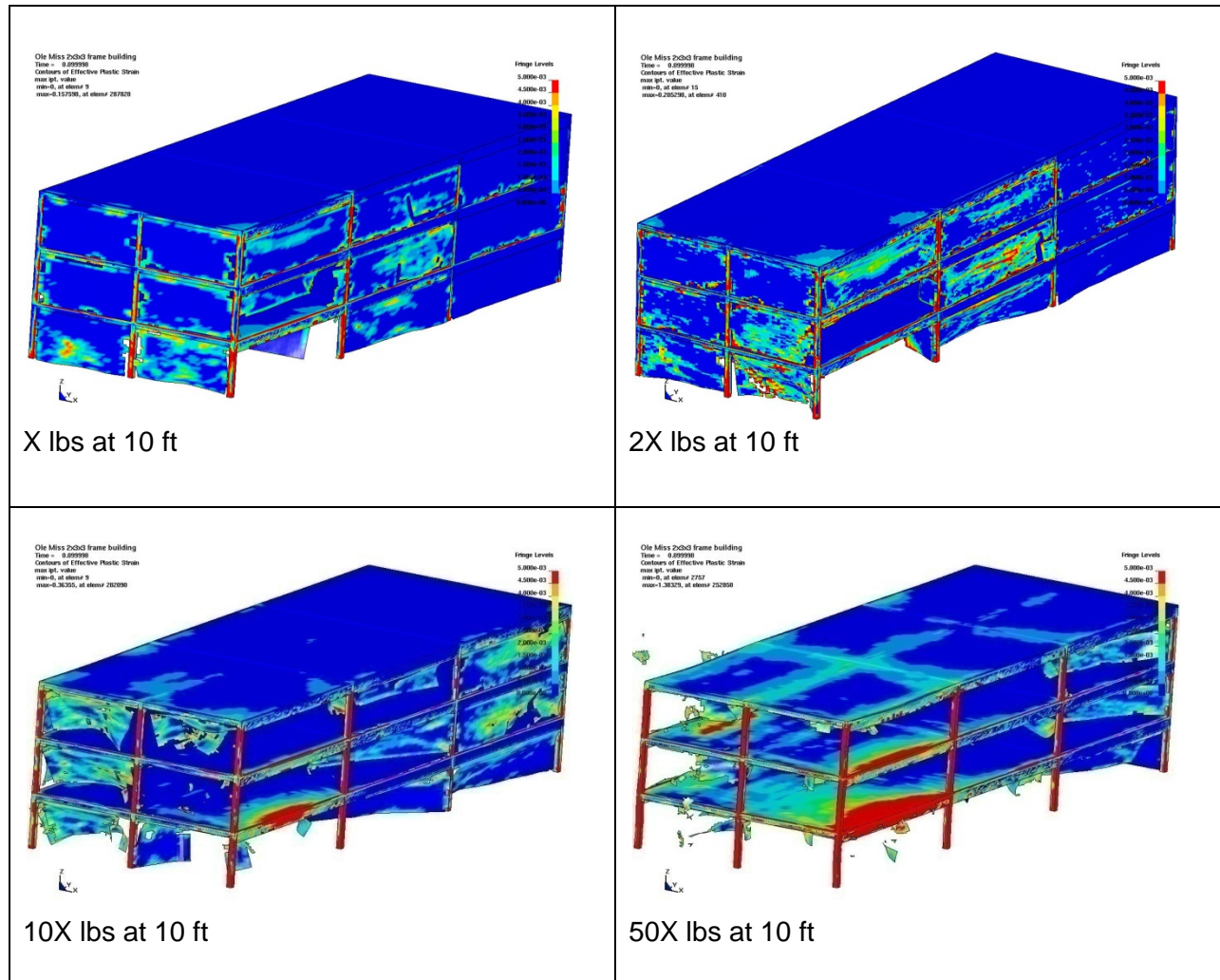


Figure 4 Effective Plastic Strain Distribution for Eccentric Side Blast Scenario.

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 (~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 inches). 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.

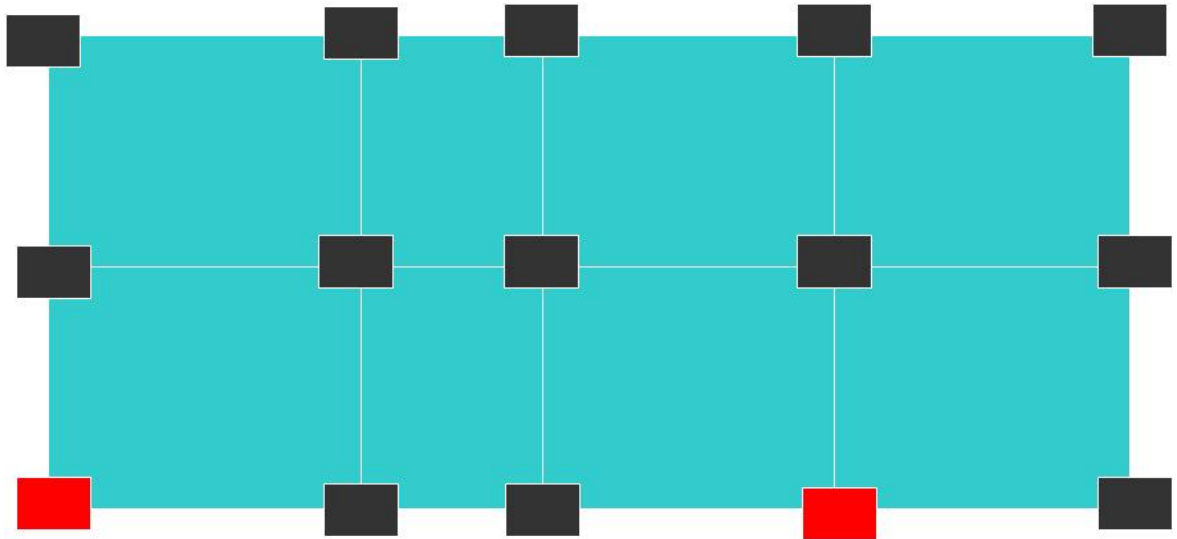
The failure sequence was as follows:

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



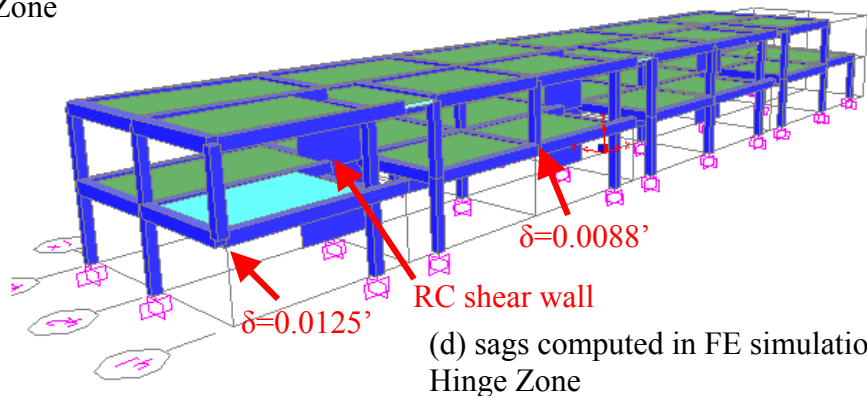
(a) Column removal choices consistent with GSA criteria



(b) corner column removal in field test Hinge Zone

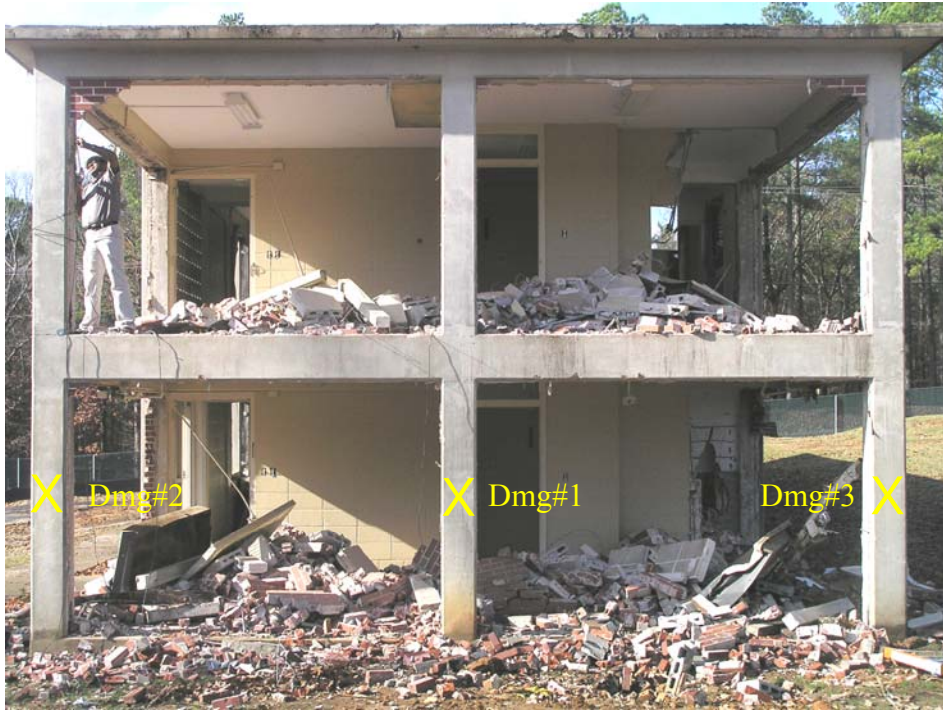


(c) corner sag measured in field test

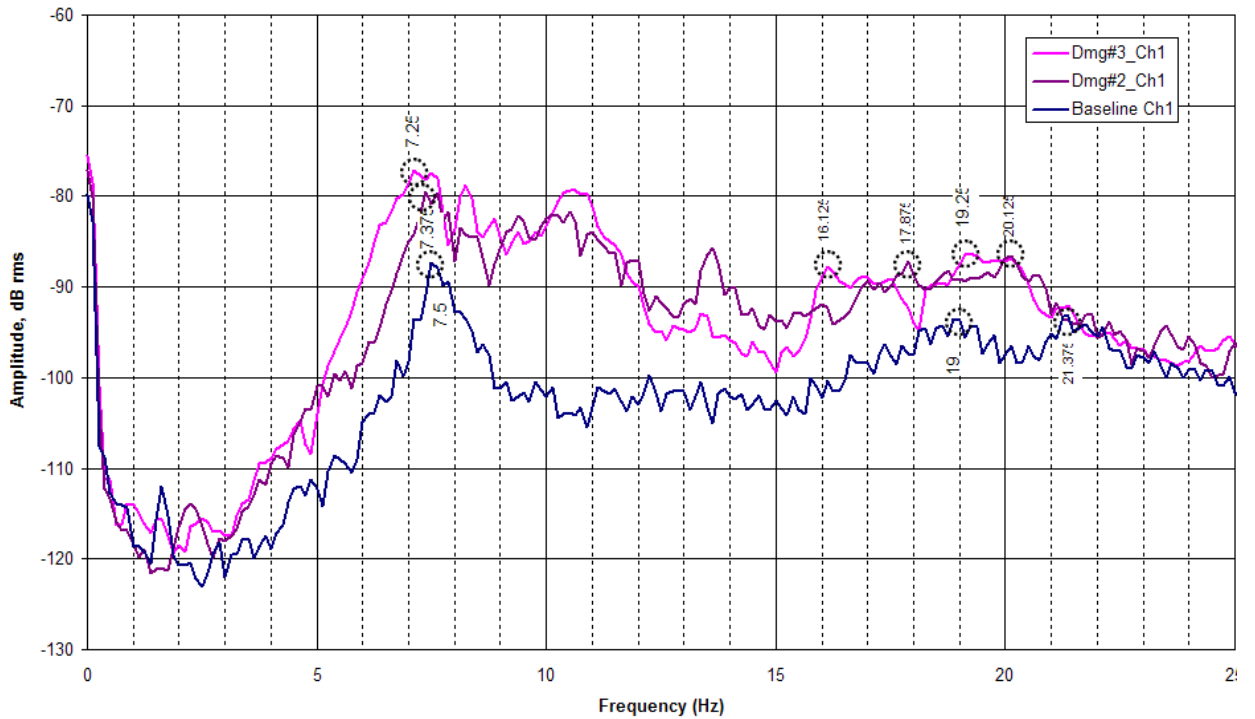


(d) sags computed in FE simulation Hinge Zone

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

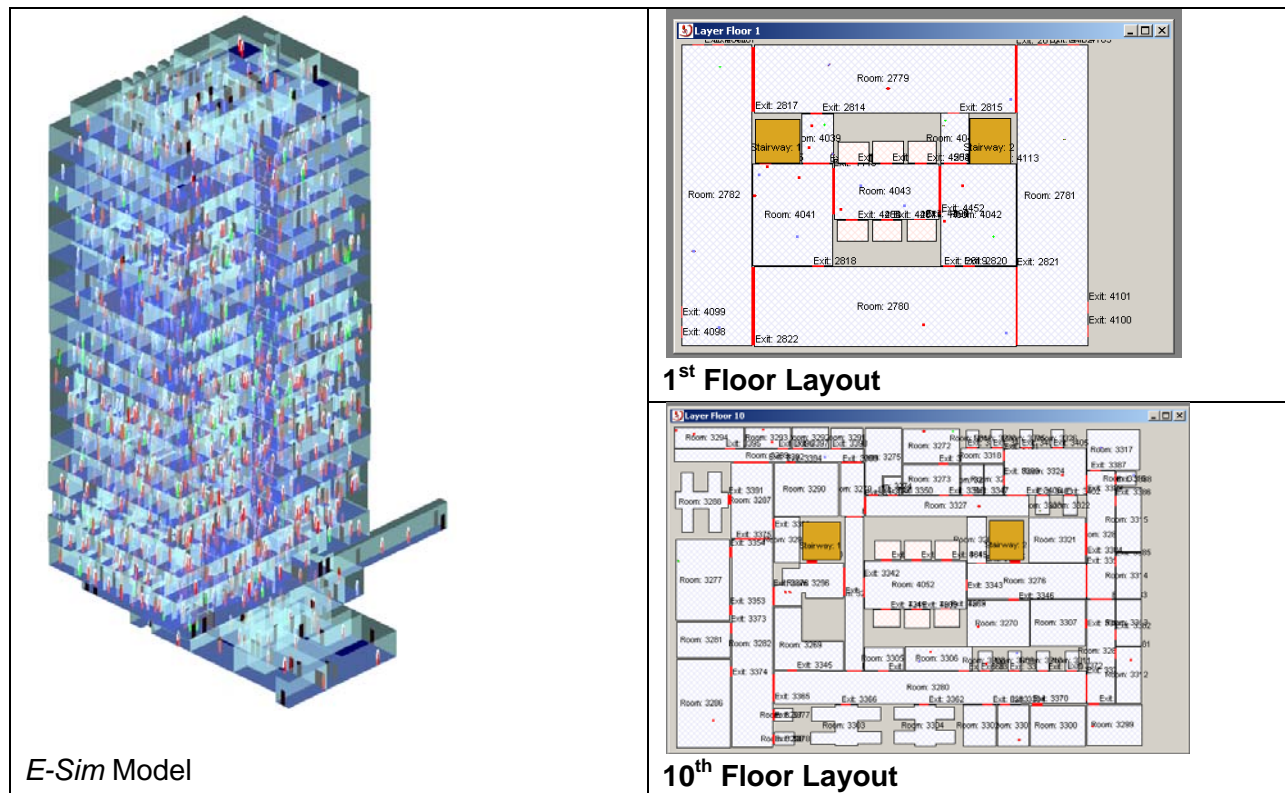


(b) FRF from vibration measurements in field tests

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, MS 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.



assumed to be upgraded to 1" laminated insulated glass units consisting of a ¼" annealed glass pane, a ½" air space, and a ¼" 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.

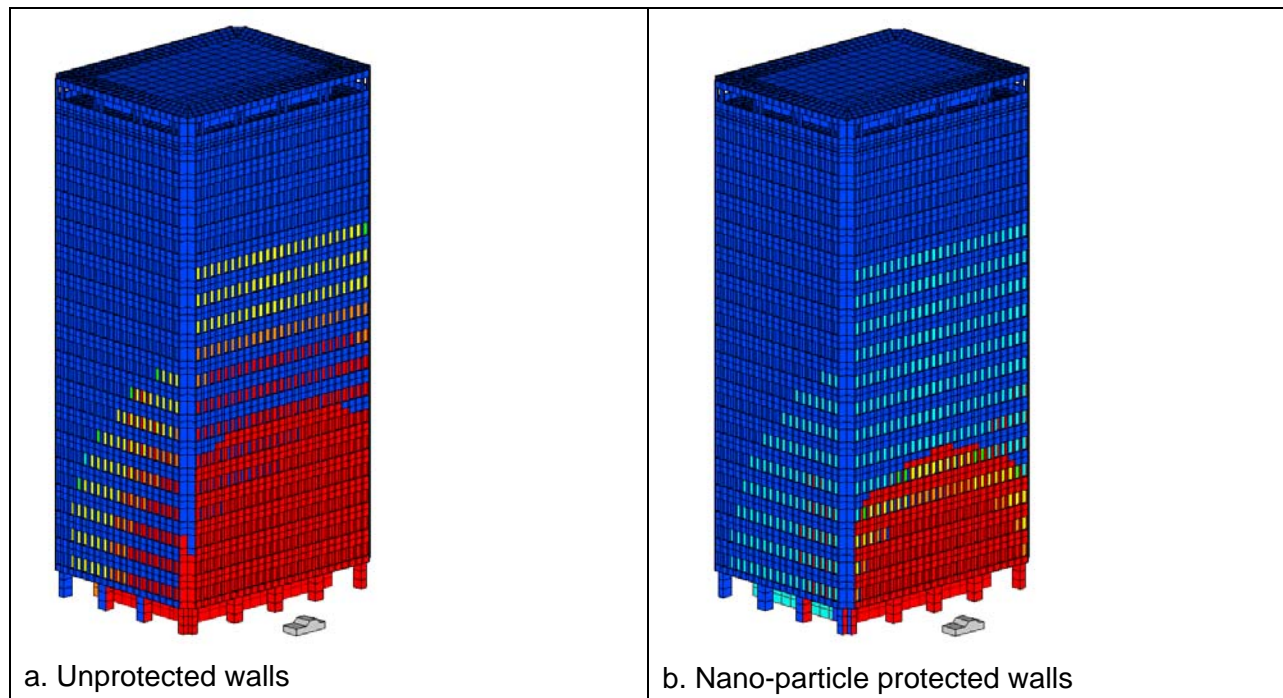


Figure 8 Simplified blast simulation to estimate extent of damage for evacuation scenarios

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.

SUGESTED STRUCTURE STABILIZATION METHOD

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

Step1 Developing data base 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.

Step2: Assessment of degree and location of damages that need immediate attention. Then prioritize need 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 is 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: 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 3 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.

References

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