



ENHANCING THE RESILIENCE OF ACUTE CARE FACILITIES: AN OVERVIEW OF MCEER RESEARCH

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ABSTRACT

Due to the complexity of acute care facilities, and depending on the extent of seismic deficiencies in any specific hospital, considerable investment may be required to ensure that an acute care facility remains operational following an earthquake. The extensive resources that would be required to achieve such a level of resilience would likely not be available at the onset, and activities to upgrade the facilities would have to be staggered over many years. Ideally, using the limited resources available at any time along this multi-year upgrading process, the objective would be to first make the investments that provide the largest enhancements to seismic resilience, and to sequence all subsequent investments following the same logic. This approach presents a significant challenge to decision makers and their specialist consultants, as there is no integrated tool that could support such a decision on factual engineering data. Note that within the spectrum of possible decisions, building new facilities must also be considered. This paper summarizes the research conducted at the Multidisciplinary Center for Earthquake Engineering (MCEER) aimed at providing such integration for enhancing the seismic resilience for acute care facilities.

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Introduction

MCEER's hospital research thrust is structured such that efforts aimed at the development of seismic response modification technologies provide data that can be used in integrated decision engines. This research thrust therefore addresses research needs for advanced seismic retrofit technologies that can provide effective solutions for acute care facilities, and research needed to formulate the integrated decision support systems that would be required to identify the most appropriate seismic mitigation actions, taking into account both engineering issues (structural and nonstructural) and organizational constraints (technical and organizational dimensions of resilience). It is important to note that the objective of this research endeavor is not to produce decision-making software, but rather to develop sound engineering concepts and data that could be used both to produce such software, and to retrofit acute care facilities or to build new ones.

Data from past earthquakes as well as engineering experience demonstrates that functionality of a hospital building can be lost due to structural failure, geotechnical failure, or damage to nonstructural building components (i.e., medical equipment). Furthermore, these are closely inter-related as damage to nonstructural building components, for example, is directly tied to structural response. In other words, modifying structural response solely for the purpose of reducing damage to the structure may have positive or negative impacts on the seismic performance of nonstructural building components. Therefore, the MCEER hospital research thrust focus on the integrated issues of performance, including both structural and nonstructural systems and components and their functionality.

Development of Advanced Technologies for Improving Seismic Performance of Hospitals

MCEER's hospital research thrust led to the development of advanced technologies to enhance the seismic performance of foundations, structures, and nonstructural components. Some of the various systems being investigated by MCEER investigators are briefly summarized below.

Studies on Metallic Energy Dissipation Systems

MCEER investigated the seismic performance of Steel Plate Walls (SPW) designed and fabricated using low yield strength (LYS) steel panels and Reduced Beam Sections (RBS) added to the beam ends in order to force all inelastic action in the beams to those locations (Bruneau and Berman 2003). Four LYS SPW specimens were designed tested cyclic loading. Two specimens had solid panels while the remaining two provided utility access through the panels by means of cutouts. One specimen consisted of a panel with a total of twenty holes, or perforations, each with a diameter of 200mm. The other specimen was a solid panel, with the top corners of the panel cutout and reinforced to transmit panel forces to the surrounding framing, as shown in Fig. 1a. A typical resulting hysteretic curve is shown in Fig. 1b. SPW buildings with low yield steel webs appear to be a viable option for use in resistance of lateral loads imparted during seismic excitation.

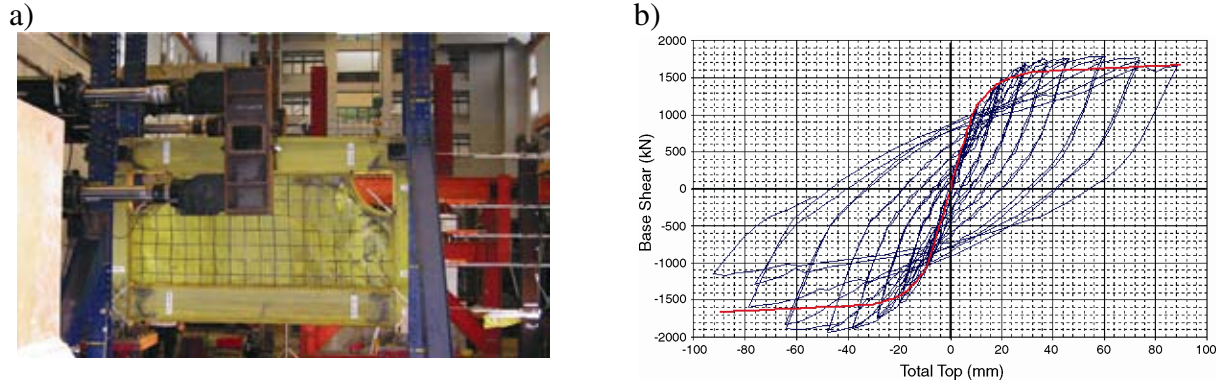


Figure 1. Test SPW specimen, a) Specimen with cutout corners to accommodate nonstructural systems, b) Typical hysteresis loops for solid panel specimen.

Studies on the Response of Nonstructural Systems in Structures with Seismic Isolation and Damping Systems

It is desirable, but not always achievable, to design hospitals for Performance Level of either Immediate Occupancy or Operational. Seismic isolation and energy dissipation or damping, particularly as described in the 2000 and 2003 NEHRP Recommended Provisions for Seismic Regulations (FEMA 2001, 2004), may be the only proven construction technologies that can achieve these performance objectives. With the verification of accuracy of methods of analysis of secondary systems in structures with seismic isolation and damping systems, MCEER investigators performed studies of the response of secondary systems with the purpose of (a) providing a comparison of performance of secondary systems in structures designed with contemporary seismic isolation and damping systems having a range of design parameters, and (b) providing guidelines on the selection of seismic isolation and damping hardware for achieving specific performance levels. Analyses have been completed for structures with damping systems and are on-going for seismically isolated structures. The assessment of performance is based on response quantities of points of attachment of secondary systems (neglecting the interaction of the structure and the secondary systems), which include peak accelerations, peak velocities and spectral accelerations over a wide range of frequencies, as well as inter-story drifts.

Figure 2 illustrates two frames that represent part of the lateral force resisting system of two buildings. Both frames meet the criteria of the 2000 (also 2003) NEHRP recommended provisions for buildings without (frame on the left) and with damping systems (frame on the right, damped at 10% of critical). Note the substantial differences in the properties of the two frames (in terms of period T_1 and yield strength V_y).

Figure 3 presents calculated average (among 20 analyses) 5%-damped floor response spectra of the undamped building, and of the building with the NEHRP-compliant damping system (3S-LV-10%, that is a linear viscous damping system providing a damping ratio of 10% in the first mode), as well other damping systems: two viscous systems designated LV-20% (a linear viscous system providing 20% damping ratio in the first mode), NLV-10% (a nonlinear viscous damping system providing an effective damping ratio of 10% in the first mode), and a yielding steel system, designated as YD. It should be noted that the undamped structure, the damped structure with the yielding steel system and the damped structures with the viscous systems at

10% effective damping just meet the NEHRP criteria for drift. The damped structure with the viscous system at 20% effective damping exceeds the NEHRP criteria for drift.

The results presented in Fig. 3 are valid for an excitation with far field characteristics and stiff soil conditions. However, similar results were obtained with near-field motions and motions representative of soft soils. The results on floor acceleration response spectra and on floor velocities (not presented here) demonstrate clear advantages of certain, but not all, damping systems.

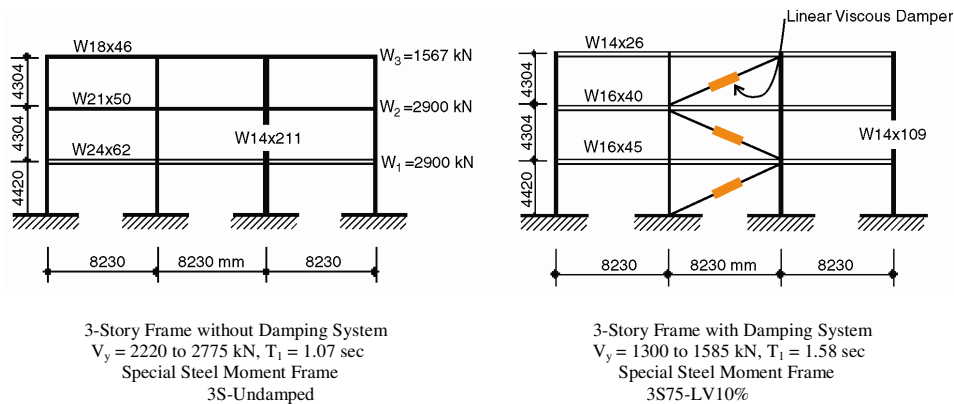


Figure 2. Example of undamped (left) and damped frames (right).

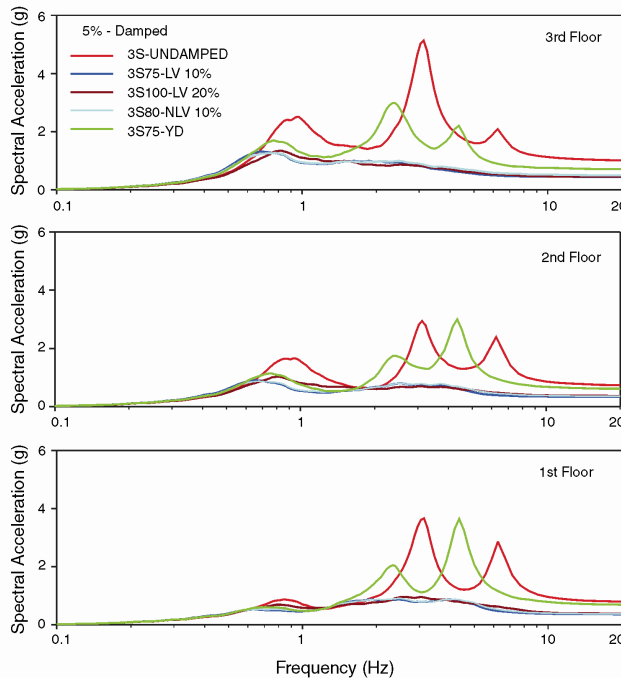


Figure 3. Floor response spectra in damped and undamped structures.

Results of this nature are currently being produced by MCEER investigators for a range of structural systems, damping systems, isolation systems, and ground motion characteristics. The

analysis also includes determination of the upper and lower bounds of the mechanical properties of the damping and isolation hardware, and use of these bounds in the analysis.

Studies on Self-Centering Systems

With current seismic design approaches, most structural systems, including those for hospital buildings, are designed to respond beyond the elastic limit and eventually to develop a mechanism involving ductile inelastic response in specific regions of the structural system. Although seismic design aimed at inelastic response is very appealing, particularly from the initial cost stand point, regions in the principal lateral force resisting system will be damaged and may need repair in moderately strong earthquakes and may be damaged beyond repair in strong earthquakes. While the principle of mitigating loss of life in a strong earthquake still prevails, resilient communities require mission-control buildings, including hospital facilities, to survive a moderately strong earthquake with relatively little disturbance to business operation. The cost associated with the loss of business operation, damage to structural and non-structural components following a moderately strong earthquake can be comparable, if not greater, to the cost of the structure itself. This implies that repairs requiring loss of business continuity should be avoided in small and moderately strong events. These issues have led the development in recent years of structural systems that possess self-centering characteristics that are economically viable alternatives to current lateral force resisting systems.

Although several self-centering structural systems using shape memory alloys, or fluids constraint in specially build containers or spring loaded friction systems have been proposed, the Post-Tensioned Energy Dissipating (PTED) steel frame (Christopoulos et al. 2002) shown in Fig. 4 is particularly appealing for hospital buildings.

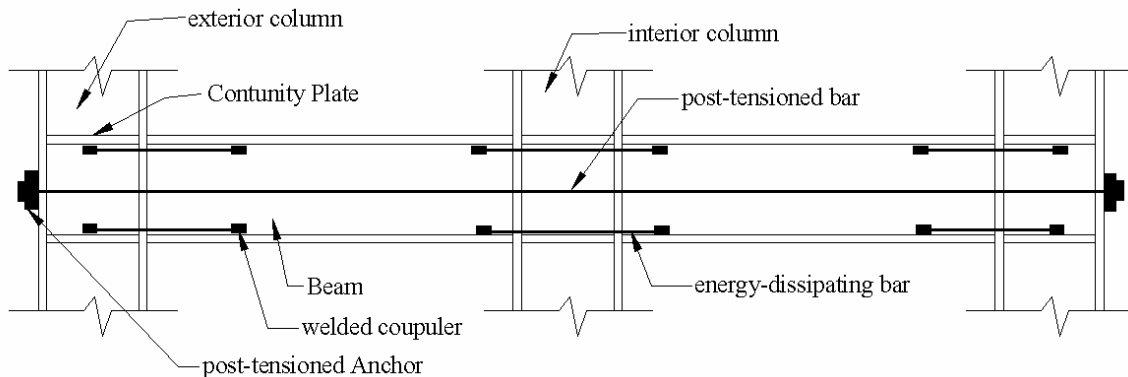


Figure 4. Concept of PTED moment-resisting steel frames.

In this system, unlike traditional moment-resisting frames, the beams and columns are not welded together. As shown in Fig. 4, a post-tension (PT) self-centering force is provided at each floor by high strength bars or tendons located at mid-depth of the beam. Four symmetrically placed energy-dissipating (ED) bars are also included at each connection to provide energy dissipation under cyclic loading. These ED bars are threaded into couplers which are welded to the inside face of the beam flanges and of the continuity plates in the column for exterior connections and to the inside face of adjacent beam flanges for interior connections. Holes are introduced in the column flanges to accommodate the PT and ED bars. To prevent the ED bars

from buckling in compression under cyclic inelastic loading, they are inserted into confining steel sleeves that are welded to the beam flanges for exterior connections and to the column continuity plates for interior connections. The ED bars are initially stress-free since they are introduced into the connection after the application of the PT force.

MCEER investigators are evaluating the seismic response of structural systems incorporating flag-shaped hysteretic structural behavior, with self-centering capability. For a system with a given initial period and strength level, the flag-shaped hysteretic behavior will be fully defined by a post-yielding stiffness parameter and an energy-dissipation parameter. Parametric studies are being conducted to determine the influence of these parameters on seismic response, in terms of displacement ductility and absolute acceleration, which are also demand parameters for nonstructural components. As shown in Fig. 5, the responses of the flag-shaped hysteretic systems are being compared against the responses of similar bilinear elasto-plastic hysteretic systems, representative of traditional yielding structural systems.

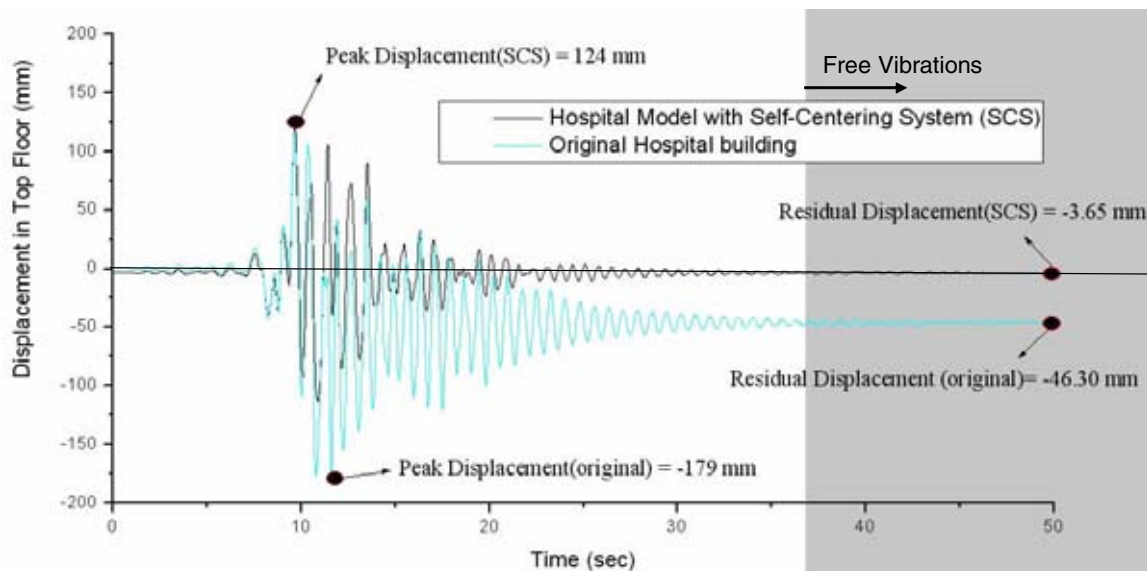


Figure 5. Seismic Response PTED and Conventional Steel Framed Hospital Building.

Research Integration with Nonstructural Building Components

The research integration centered on the response of nonstructural building components, which represent the bulk of the investment in acute care facilities, is now maturing at MCEER. Selected noteworthy recent research accomplishments are summarized below.

An extensive online database of nonstructural damage suffered by hospitals in past earthquakes was compiled (see <http://mceer.buffalo.edu/publications/reports/docs/99-0014/default.asp>). This is the only such database in existence in the public domain, and as such, provides a valuable perspective on the seismic vulnerability of hospital contents.

The fragility of some types of equipment was quantified through extensive shake table testing. Restraint designs for equipment were developed, from simple mitigation techniques to more

advanced energy dissipation approaches. This experimental fragility research has now moved towards heavier equipment, such as HVAC equipment, as shown in Fig. 6. This experimental work has generated a great interest among equipment manufacturers.

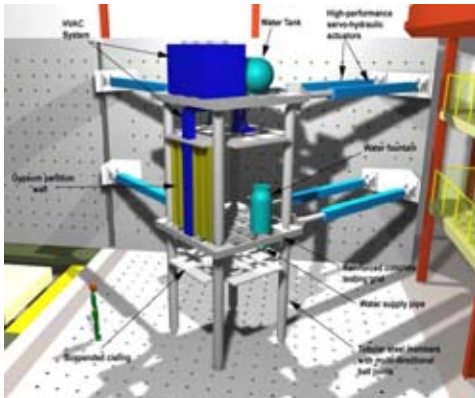
The experimental performance evaluation of pressurized piping distribution systems through shake table experiments is on-going at MCEER. The general layout of the system was designed in collaboration with the Office of Statewide Health Planning and Development (OSHPD). Realistic acceleration levels for braced and unbraced piping systems along with their failure modes were identified. Using a test-bed demonstration hospital, realistic floor accelerations were developed for various hazard levels and were used to conduct shake table experiments of various piping systems.



Figure 6. Shake table testing of HVAC equipment on acoustic isolation/restraint systems.

Through a creative and original highly modular and versatile framework and substantial leveraging achieved by enhancing/upgrading the existing equipment available at the University at Buffalo NEES Facility (UB-NEES), MCEER investigators (Retamales et al. 2006) have designed a National Testing Facility for Nonstructural Components that will allow integrated experimental and analytical research to investigate the seismic performance of nonstructural components. The Nonstructural Components Simulator (NCS) consists of actuators and special modular testing platforms that make it possible to answer the challenges of dynamically replicating the large displacements, velocities, and accelerations to which equipment and non-structural components are typically subjected during earthquakes, as well as the interactions of this equipment with the structural systems (and other equipments). This new facility will empower MCEER investigators and practitioners, particularly those involved in MCEER's hospital research thrust, to think at the systems level and to understand, quantify and control the seismic response of non-structural components as part of the total building system.

a)



b)



Figure 7. Nonstructural Component Simulator (NCS) at the University at Buffalo, a) bi-axial configuration, b) uni-axial configuration

Integrated design of structural and nonstructural components in acute care facilities are also being investigated through shake table testing. Figure 8 shows, for example, photographs of a 3-story steel frame incorporating Buckling Restrained Braces (BRB) to reduce the structural inter-story drifts and a floor isolation system to reduce floor accelerations.



Figure 8. Shake table testing of a 3-story steel frame incorporating Buckling Restraint Braces (BRB) and floor isolation system.

Methodologies for Integrated Decision-Making Platforms

Two decision-support platforms have been identified as having the potential to integrate the key issues identified as part of MCEER's Hospital Thrust Area. The research focus on advancing the development of each of these two platforms to the proof of concept stage, demonstrating how the multiple dimensions of enhancing resilience for acute care facilities can be taken into account and integrated.

The first MCEER decision-making platform, developed at MCEER, investigates the fragility approach and how multiple systems can be integrated within that framework (Kafali and Grigoriu 2004). This platform has been embodied into a Rehabilitation Decision Analysis Toolbox (RDAT) through a user friendly MATLAB interface. This tool is now available through the MCEER User's Network (http://civil.eng.buffalo.edu/users_ntwk/index.htm).

The second decision-making platform developed at MCEER investigates the use of an evolutionary analysis procedure for structural systems incorporating advanced protective technologies in an uncertain seismic environment that can integrate multiple flexible constraints and rules including non-engineering organizational and socio-economic constraints. This evolutionary-based decision-support platform has been embodied in year 8 into the PC-based Evolutionary Aseismic Design and Retrofit (EADR) software (Dargush and Sant 2005).

This evolutionary-based decision-support platform is supported by the social science work aimed at investigating how quantitative social science knowledge can be integrated into engineering decision-support models. Integration of engineering requirements, organizational rules and constraints representative of the environment, and issues that must be considered by acute care facilities in California are being integrated as proof-of-concept. As part of this effort, a case study on the State Bill 1953 (SB 1953) in California has been recently completed (Alesch et al. 2005). This SB 1953 case study provided a unique opportunity to document the obstacles to the implementation of effective seismic mitigations measures for hospitals and the associated means to overcome those obstacles.

Conclusions

This paper has described briefly some of the integrated research currently underway at MCEER to enhance the seismic resilience of structural and nonstructural systems and components in acute care facilities from the effects of earthquakes. This innovative work promises to deliver robust and applicable decision support methodologies for enhancing the seismic resilience of acute care facilities.

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References

- Alesch, D.J., Arendt, L.A. and Petak, W.J. *Seismic Safety in California Hospitals: Assessing an Attempt to Accelerate the Replacement of Seismic Retrofit of Older Hospital Facilities*. Technical Report MCEER-05-0006, Multidisciplinary Center for Earthquake Engineering Research, University at Buffalo, State University of New York, Buffalo, NY,
- Bruneau, M., and Berman, J., 2003. *Plastic Analysis and Design of Steel Plate Shear Walls*. ASCE Journal of Structural Engineering, 129(11), 1448-1456.

- Christopoulos, C., Filiatrault, A., Folz, B., and Uang, C-M., 2002. *Post-Tensioned Energy Dissipating Connections for Moment-Resisting Steel Frames*. ASCE Journal of Structural Engineering, 128(9), 1111-1120.
- Dargush, G.G., and Sant, S. 2005. *Evolutionary Aseismic Design and Retrofit of Structures with Passive Energy Dissipation*. Earthquake Engineering & Structural Dynamics, 34(13), 1601-1626.
- FEMA, 2001. NEHRP Recommended Provisions for Seismic Regulations for New Buildings and other Structures-2000 Edition. FEMA 368, Federal Emergency Management Agency Washington, D.C.
- FEMA, 2004, NEHRP Recommended Provisions for Seismic Regulations for New Buildings and other Structures-2003 Edition. FEMA 440, Federal Emergency Management Agency, Washington, D.C.
- Kafali C. and Grigoriu M., 2004. *Seismic Fragility Analysis*. 9th Joint Specialty Conference on Probabilistic Mechanics and Structural Reliability, Albuquerque, New Mexico.
- Retamales, R., Mosqueda, G., Filiatrault, A., and Reinhorn, A. 2006. *Experimental Study on the Seismic Behavior of Nonstructural Components Subjected to Full-Scale Floor Motions*. 8th National Conference on Earthquake Engineering, San Francisco, CA.