Mceer's Research on The Seismic Response Modification of Structural and Non-Structural Systems and Components in Hospitals

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Abstract

This paper describes the research currently underway at the Multidisciplinary Center for Earthquake Engineering Research (MCEER) on the applications of a broad range of seismic response modification technologies to protect structural and nonstructural systems and components in acute care facilities from the effects of earthquakes. An important component this research is to establish a relationship

between the performance of nonstructural components and structural demands in order to optimize and harmonize performance objectives between structural and nonstructural systems and components in acute care facilities. Results of analytical and experimental studies are being used in fragility studies to probabilistically quantify the relative merits and potential benefits to structural and nonstructural component of implementing these technologies. Eventually, the results will be quantified and included in decision support methodologies that integrate both engineering and social science aspects.

Introduction

Achieving a given target seismic resiliency for acute care facilities require the harmonization of the performance levels between structural and nonstructural components. Even if the structural components of a hospital building achieve an immediate occupancy performance level after a seismic event, failure of architectural, mechanical, or electrical components of the building can lower the performance level of the entire building system. This reduction in performance caused by the vulnerability of nonstructural components has been observed in several buildings during the recent 2001 Nisqually earthquake in the Seattle-Tacoma area (Filiatrault *et al*., 2001) and during several other earthquakes that have occurred in the last 40 years (Ayres *et al*., 1973; Ayres and Sun, 1973; Ding *et al*., 1990; Reitherman, 1994; Reitherman and Sabol, 1995; Gates and McGavin, 1998). The investment in nonstructural components and building contents in hospitals is far greater than that of structural components and framing. Therefore, it is not surprising that in many past earthquakes, losses from damage to nonstructural building components exceeded losses from structural damage. This was clearly the case in the recent 2001 Nisqually earthquake (Filiatrault *et al*., 2001). Furthermore, failure of nonstructural building components could become safety hazards or could affect the safe movement of occupants evacuating or rescue workers entering buildings.

In comparison to structural components and systems, there is still relatively limited information on the seismic performance of nonstructural components. Basic research work in this area has been sparse, and the available codes and guidelines (FEMA 1994, ASCE 2000, Canadian Standard Association 2002) are usually, for the most parts, based on past experiences, engineering judgment, and intuition, rather than on experimental and analytical results. Often, design engineers are forced to start almost from square one after each earthquake event: observe what went wrong and try to prevent repetitions. This is a consequence of the empirical nature of current seismic regulations and guidelines for nonstructural components.

Retrofitting hospitals using seismic response modification technologies can make it possible to harmonize the performance of structural and nonstructural components in order for entire acute care facilities to meet or exceed a specified resiliency level during and after an earthquake.

This paper briefly describes the research currently underway at MCEER on the development and application of seismic response modification technologies for the seismic protection of structural and nonstructural systems and components in acute care facilities. This work is innovative and important since the application of seismic response modification technologies in building structures to date has been based solely on structural performance. Only when the variations in seismic fragility of coupled structural and nonstructural components as a function of structural systems (including seismic response modification technologies) and/or equipment retrofit is available that robust decision-making tools can be implemented.

Studies on Metallic Energy Dissipation Systems

MCEER recently initiated a co-operative experimental program with National Taiwan University (NTU) and National Center for Research on Earthquake Engineering (NCREE) to investigate 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. It was felt that this would promote increasingly efficient designs of the "anchor beams," defined as the top and bottom beams in a multistory frame, which "anchor" the tension field forces of the SPW infill panel.

A total of four LYS SPW specimens were designed by MCEER researchers, fabricated in Taiwan, and tested collaboratively by MCEER and NCREE researchers at the NCREE laboratory in Taiwan. The frames, consisting of 345MPa steel members, were 4000mm wide and 2000mm high, measured between member centerlines. The infill panels were 2.6mm thick, LYS, with an initial yield of 165MPa. 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. 1. The intention of the final two specimens is the accommodation of penetrations by utilities necessary for building operation.

All specimens were tested using a cyclic, pseudo-static loading protocol similar to ATC-24. Loading history was displacement-controlled, and applied horizontally to the center of the top beam using four actuators. A typical resulting hysteretic curve is shown in Fig. 2.

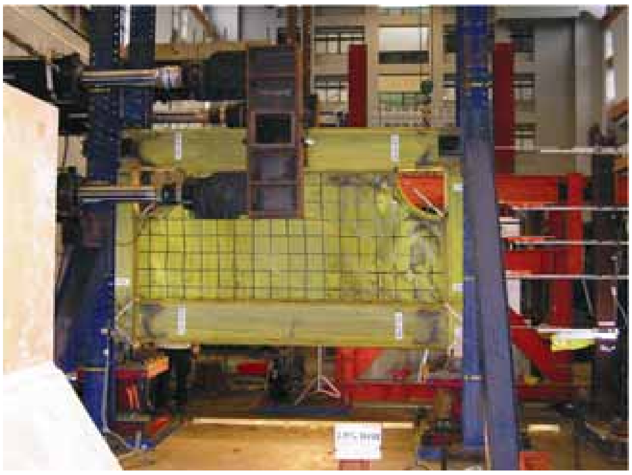


Figure 1: SPW Specimen with Cutout Corners to Accommodate Nonstructural Systems.

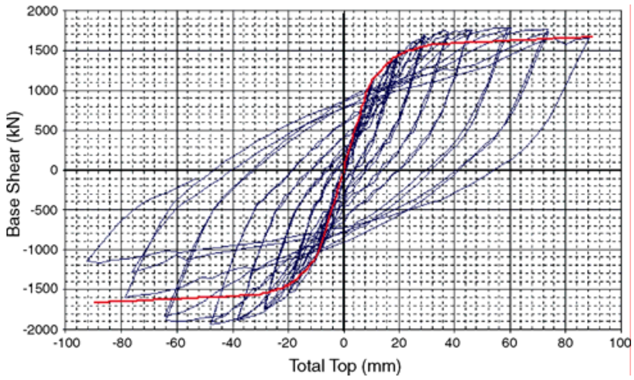


Figure 2: Hysteresis Loops for Solid Panel Specimen S1.

SPW buildings with low yield steel webs appear to be a viable option for use in resistance of lateral loads imparted during seismic excitation. The lower yield strength and thickness of the tested plates result in a reduced stiffness and earlier onset of energy dissipation by the panel as compared to conventional hot-rolled plate. The perforated panel specimen shows promise towards alleviating stiffness and over-strength concerns using conventional hot-rolled plates. This option also provides access for utilities to penetrate the system, important in a retrofit situation, in which building use is pre-determined prior to SPW implementation. The reduced beam section details in the beams performed as designed, as shown in Fig. 3. Use of this detail may result in more economical designs for beams "anchoring" an SPW system at the top and bottom of a multi-story frame. On-going research is focusing on developing reliable models that can capture the experimentally observed behavior, and investigating the benefits of this system on enhancing the seismic performance of nonstructural components, using the MCEER west-coast demonstration hospital (Bruneau and Berman, 2003) for that purpose.

Figure 3: Buckled Panel and RBS Yielding of SPW Specimen.

Studies on The Resposne of Non-Structural 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. Early studies showed promising performance for application of such technologies (Juhn *et al*., 1992). Yet, methodologies for the design of nonstructural systems to achieve these performance levels are not available.

In order to develop methodologies for the design of hospitals for the immediate occupancy and operational performance levels, it is necessary that (a) performance limits for nonstructural systems are established, and (b) the dynamic response of non-structural systems is determined. Recently completed studies on the behavior of structures with seismic isolation and damping systems (Wolff and Constantinou, 2004) resulted in (a) a wealth of experimental results on systems of contemporary design, including data related to secondary system response, and (b) comparisons of analytical and experimental responses that demonstrate capability of nonlinear response history analysis methods to predict the response of nonstructural (secondary) systems.

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.

The approach followed was based on dynamic analysis of structures with the following attributes:

(a) Range of structural systems with different stiffness (period) characteristics.

(b) Range of seismic isolation and damping systems, including lead-core, elastomeric, friction pendulum, linear viscous, nonlinear viscous and yielding steel systems.

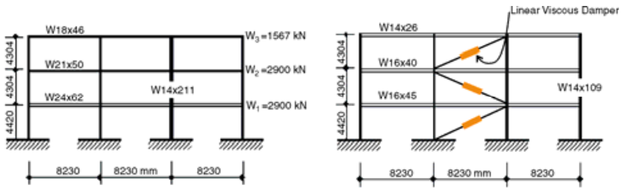
(c) Range of parameters for each system, including parameters for upper/lower bound analysis for each particular system.

(d) Range of seismic excitations, including far-field, near-field and soft-soil motions, all represented by suites of motions having a representative average spectrum.

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 4 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 5 presents calculated average (among 20 analyses) 5%-damped floor response spectra of the undamped building (red line), 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.



3-Story Frame without Damping System
V_y = 2220 to 2775 kN, T_1 = 1.07 sec
Special Steel Moment Frame
3S-Undamped

3-Story Frame with Damping System
V_y = 1300 to 1585 kN, T_1 = 1.58 sec
Special Steel Moment Frame
3S75-LV10%

Figure 4: Example of Undamped (Left) and Damped Frames (Right).

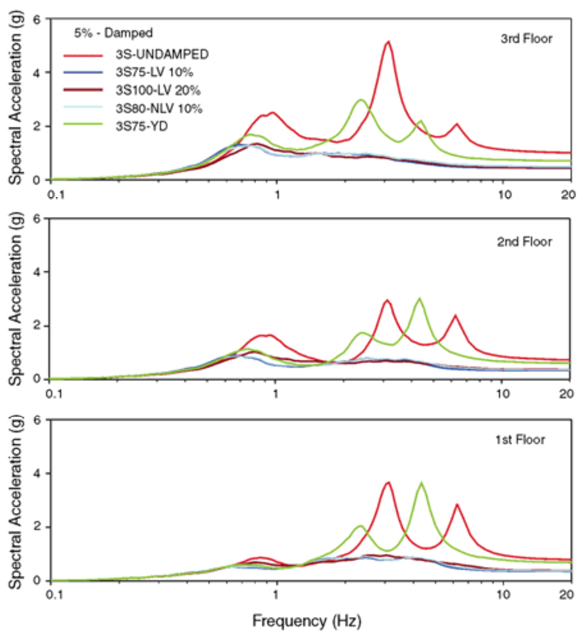


Figure 5: Floor Response Spectra in Damped and Undamped Structures.

The results presented in Fig. 5 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.

Results of this nature are currently produced by MCEER researchers 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 Real Time Structural Parameter Modification Systems

In an attempt to modify the response of the global structural system a new method for modification of response was suggested to extend methodologies proposed in the last decade (Soong, 1990). The RSPM (Real-time Structural Parameter Modification) is a semi-active nonlinear control system for reducing seismic responses of structural and nonstructural systems and components. Figure 6 illustrates the operation of this innovative system developed by MCEER researchers. The system includes a passive damper and a controlled stiffness unit. The passive damper is always engaged to dissipate energy, but the stiffness unit is connected or disconnected based on a pre-set threshold. It is disconnected initially until a response threshold value—termed the open distance, is reached. If the relative displacement (positive or negative) becomes larger than the open distance, the stiffness unit is engaged to control the response. If, at any instant, the displacement becomes smaller than the threshold, the RSPM stiffness unit is disconnected. The semi-active control mechanism is activated only when the stiffness unit is connected. The devices are normally combined as a pair of tension and compression units working as a push-and-pull set.

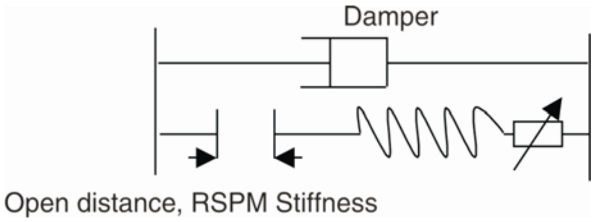


Figure 6: Combined RSPM and Passive Damping Hybrid Control System.

MCEER research has been focused on the potential control benefit of the semi-active system over passive systems such as viscous dampers. The control effect of the semi-active system is targeted to seismic response reduction of nonlinear systems. To evaluate the seismic response behaviors in the linear and non-linear range, MCEER researchers have developed an index ratio of displacement incremental rate to the velocity incremental rate with respect of elastic responses. The mathematical definition of this ratio η is given below:

$$\eta = \frac{\max(d_{non}(t))/\max(d_{lin}(t))}{\max(v_{non}(t)/\max(v_{lin}(t))}$$

where d_{non} and d_{lin} are the inelastic and elastic displacement responses respectively; v_{non} and v_{lin} are the inelastic and elastic velocity responses respectively.

Using one-story and a three-story frame models, numerical studies under different ductility and natural frequency show that η is greater than unity, which means that the displacement responses increase much faster than the velocity responses. This behavior confirms that the displacement-based control is more effective than the velocity-based control in inelastic structural response reduction. Figure 7 shows the variation of η as a function of ductility for the bilinear inelastic responses of a three-story frame model. The study has also revealed that the change in η is strongly influenced by the yielding pattern (e.g. bilinear, tri-linear and continuous yielding), the natural period before and after yielding, and the ductility.

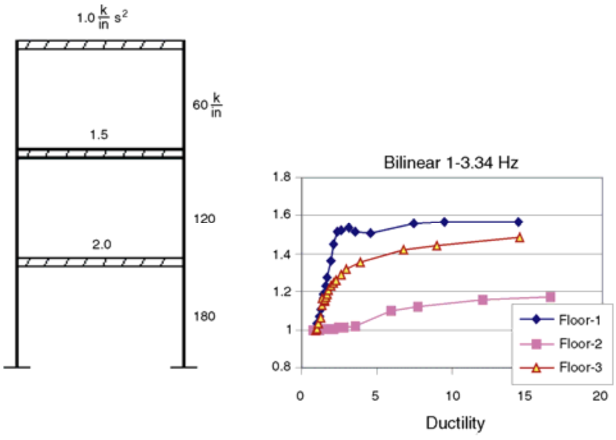


Figure 7: Variation of η with Ductility for a Three-Story Frame Model.

Figure 8 compares a passive damper system with a hybrid system (passive damping plus semi-active) in the three-story frame model response control. The damping device has been chosen as a linear viscous damper, for which the damping ratio is 15%. In the hybrid control system, an equivalent 15% of the structural stiffness has been assigned to the RSPM control along with an equivalent damping ratio 15% contributed from the hybrid device. The selection of the hybrid control parameters is based on the actual configuration of the devices. Since RSPM is designed as an improvement of the passive damper, a semi-active component is generally added to enhance the performance of the passive damper. To show the effect of the semi-active component in the seismic response control, the comparison is carried for a wide response range including: the elastic response, the yielding point and the large ductility range. Figure 8 shows that the displacement based semi-active control has non-uniform control effect. In general, at each structural yielding point, the hybrid control effect outperforms the damping system, as ductility increases, the hybrid control effect also increases faster than the passive damping system.

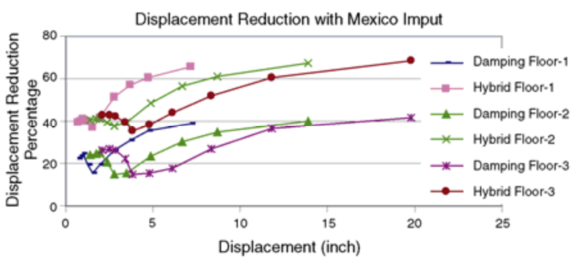


Figure 8: Seismic Response of Passive Damper and Hybrid Control System.

In summary, semi-active control strategies may be able to provide a larger control capability for seismically induced structural response reduction. In particular, they are better able to balance the difficult structural control requirements, such as limiting acceleration levels and controlling story responses, thus reducing structural response in both elastic and inelastic ranges. It is hopeful that the semi-active control, together with other structural response technologies, will provide a much better floor response control for both linear and nonlinear response range. In turn, the reduced floor responses will result in less nonstructural component damage.

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.

Figure 9 shows the characteristic flag-shaped seismic response of such a self-centering system. The amount of energy dissipation is reduced compared to that of a yielding system, but, more importantly, the system returns to the zero-force zero-displacement point at every cycle and at the end of the seismic loading.

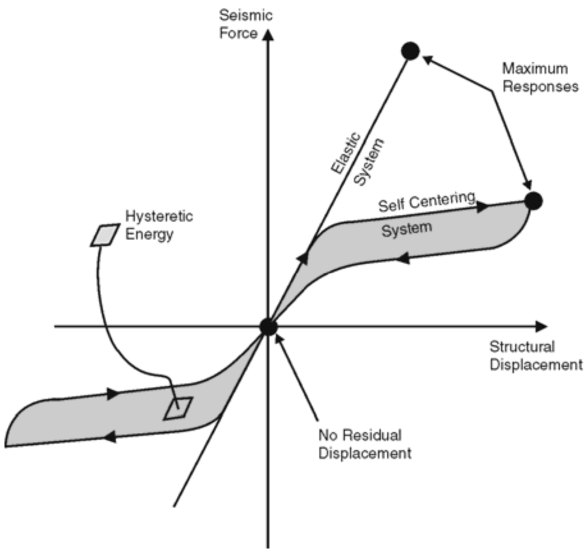


Figure 9: Idealized Seismic Response of Self-Centering Structures (Christopoulos *et al.* 2002a).

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 shown in Figure 10 is particularly appealing for hospital buildings.

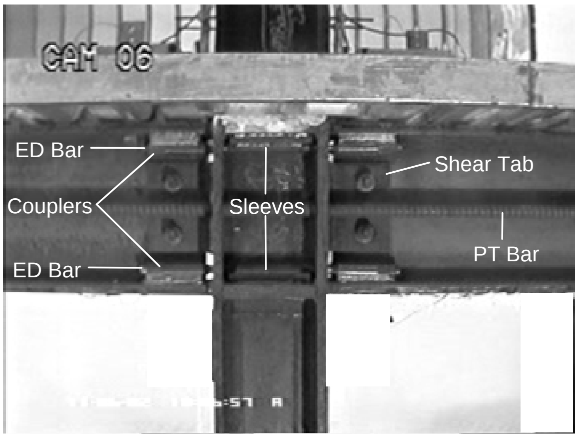


Figure 10: Concept of PTED Moment-resisting Steel Frames (Christopoulos *et al*. 2002b).

In this system, unlike traditional moment-resisting frames, the beams and columns are not welded together. As shown in Fig. 10, 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 researchers are investigating 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. The responses of the fag-shaped hysteretic systems are being compared against the responses of similar bilinear elasto-plastic hysteretic systems, representative of traditional yielding structural systems.

Studies on Advanced Composite Infill Panels

One way to retrofit hospital buildings is with innovative design of infill walls. Even though infill construction has been popular since late 19th century in seismic regions of central and eastern United States, it is not until recently that polymer matrix composite (PMC) materials have received attention. Previously structural frames infilled with unreinforced brick, concrete masonry, and structural clay tile dominated the industry. With the infrastructure of older constructed building reaching a stage where there is significant deterioration and questionable functionality, many researchers have turned to more innovative strengthening schemes to improve on the disadvantages associated with traditional strengthening techniques. These modern rehabilitation techniques are needed to help simplify the construction process by reducing time, cost and inconvenience of associated with seismic retrofitting.

Fiber reinforced polymer (FRP) materials have increasingly been evolving as a viable seismic retrofit strategy. The ability to use FRP material in the construction of infill walls is a great advantage. Prefabricated PMC infill systems have properties that can be tailored to achieve desired response. Geometric configurations are able to remain unchanged with the option to enhance structural performance by just changing fiber orientation and stacking sequence. In a structure seismically retrofitted with PMC infill walls, ductile behavior can be achieved through shear deformation of the walls instead of plastic hinge formation. This allows the functionality of structures following a seismic event due to the fact that the gravity load carrying system will not have damage that is irreparable.

This phase of the research builds upon the research of Jung (2003) and applies it to MCEER demonstrations hospitals. The main scope is to develop a simplified spring-dashpot model for the outer damping panel PMC infill system proposed so that dynamic analysis of the hospital structures can be performed with relative ease and with reduced computation time. The proposed model should produce sufficient energy dissipation and ductility while keeping floor accelerations at a minimum. The outer damping panel system is made of FRP panels with an interface containing both flexible honeycomb and solid viscoelastic materials. Figure 11 shows a detail of the system. Combining viscoelastic materials with honeycomb at the interface between panels has proven to be effective damping application and adding stiffness to the structure (Aref and Jung, 2003).

At this stage of the research, two fundamental issues are being considered: (1) the need for a robust visco-elastic model that efficiently works within dynamic analysis in ABAQUS (1997); (2) the need for optimizing the size, distribution of the panels to get the proper modification to the floor accelerations and displacements in each demonstration structure.

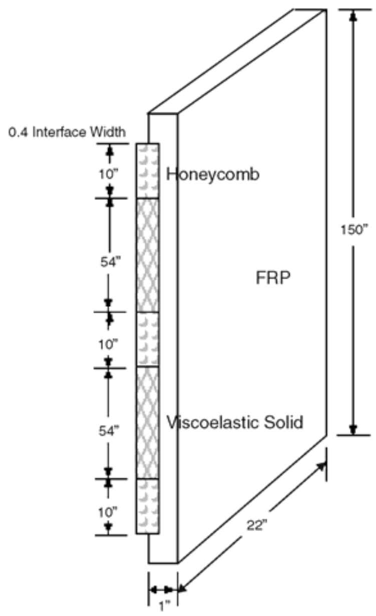


Figure 11: Details of Interface Layer of PMC Infill System.

Studies on Global Retrofit of Structures by Weakening and Damping

Another innovative approach developed by MCEER researchers to control the seismic response of structural and nonstructural systems and components consists of weakening existing structural components to reduce maximum acceleration response, while adding energy dissipation systems (dampers) to control increased deformations (Viti *et al.*, 2002). The method addresses simultaneous reduction of structure accelerations and structure deformations. The effect of the weakening method can be viewed as similar to the effects of base isolation solutions, which decrease the global acceleration response of structures while increasing overall movement of the structure. However, the weakening is not sufficient and requires control of deformations. The proposed solution requires modification of some of the structural components. The structures constructed with plain, or perforated shear walls, have usually high strength and develop large accelerations during earthquakes leading to damage of equipment and non-structural components.

Typical vulnerable hospital structures of this type are constructed mostly with walls with openings for windows or access doors (identified herein as perforated walls). In an attempt to evaluate their behavior before and after applying the retrofit suggested above a new modeling technique has been developed by MCEER researchers. According to the proposed technique it is suggested to model such walls using a combination of frame models with deep beams and column elements with rigid connection panels as shown in Fig. 12.

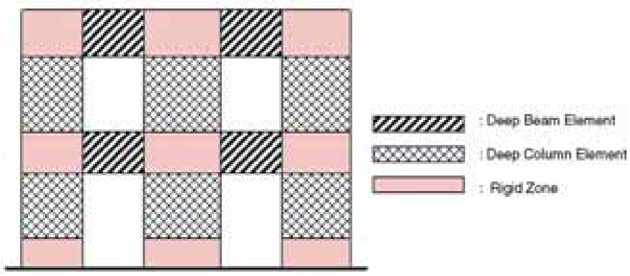


Figure 12: Model for Shear Wall with Regular Openings (Perforated Walls).

However such models for “deep” beams and columns, which exhibit a strong interaction between their bending (flexure) and shear inelastic mechanisms, are not available in customary inelastic analysis computational platforms. MCEER researchers developed such models and implemented them in the inelastic structural analysis program IDARC2D leading to a new Version (5.5) available to the MCEER Users Network and to the specialized Users Group.

An extensive verification of this approach was performed by MCEER researchers using a typical wall with openings from a Californian hospital which needs retrofit through weakening. The model of the wall was analyzed with an increasing amplitude cyclic load and the performance was recorded in terms of force displacement evolution, as shown in Fig. 13 and damage progression.

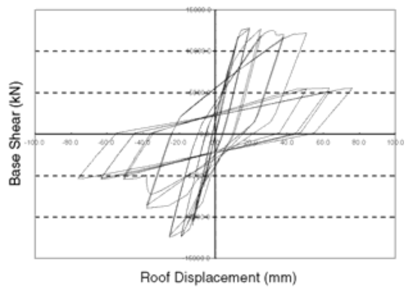


Figure 13: Global Hysteretic Response of Shear Wall with Openings.

The performance shows a sharp reduction in the force capacity of the wall due to local shear of peers between openings and some flexural yielding at first floor. The damage indices calculated by the IDARC2D Version (5.5) suggest that extensive damage is expected in the first floor although the strength of the wall is high.

The analytical tool developed MCEER researchers enable evaluation of the wall structure and provides way to determine the amount of strength reduction. The platform IDARC2D can then evaluate the influence of both weakening and the contribution of added energy dissipation systems.

Conclusions

This paper has described briefly the integrated research currently underway at MCEER to better understand the applications of various seismic response control technologies to protect 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.

Acknowledgements

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References

ABAQUS / STANDARD, Version 5.7 and 5.8., Hibbitt, Karlsson & Sorensen, Inc. Pawtucket, RI., 1997.

Aref, A. J., Jung, W. Y., 2003, "Energy–dissipating Polymer Matrix Composite Infill Wall System for Seismic Retrofitting", *J. Struct. Engrg.*, ASCE, **129**(4), 440-448.

ASCE 2000, "Prestandard and Commentary for the Seismic Rehabilitation of Buildings", FEMA-356. American Society of Civil Engineers, Reston, Virginia.

Ayres, J.M., Sun, T.Y. and Brown, F.R. 1973, "Nonstructural Damage to Buildings, in The Great Alaska Earthquake of 1964," Engineering, Division of Earth Sciences, National Research Council, National Academy of Sciences, Washington, DC, 346-456.

Ayres, J.M. and Sun, T.Y. 1973, "Nonstructural Damage, in the San Fernando, California Earthquake of February 9, 1971," US Department of Commerce, National Ocean and Atmospheric Administration, 1(B), 736-742.

Bruneau, M., and Berman, J. 2003, “Plastic Analysis and Design of Steel Plate Shear Walls,” ASCE *Journal of Structural Engineering*, Vol.129, No.11, pp.1448-1456.

Canadian Standard Association, 2002. “Guideline for Seismic Risk Reduction of Operational and Functional Components (OFCs) of Buildings, Standard CSA S832-01, Mississauga, Ontario, 105 p.

Christopoulos, C., Filiatrault, A., and Folz, B. 2002a, “Seismic Response of Self-Centering Hysteretic SDOF Systems,” *Earthquake Engineering & Structural Dynamics*, **31**(5): 1131-1150.

Christopoulos, C., Filiatrault, A., Folz, B., and Uang, C-M. 2002b, “Post-Tensioned Energy Dissipating Connections for Moment-Resisting Steel Frames,” ASCE *Journal of Structural Engineering*, **128**(9): 1111-1120.

Ding, D. and Arnold, C., Coordinators. 1990, “Architecture, Building Contents, and Building Systems,” Chapter 9 in Supplement to Volume 6: Loma Prieta Earthquake Reconnaissance Report, *Earthquake Spectra*, 339-377.

FEMA, 1994, “Reducing the Risks of Nonstructural Earthquake Damage, Practical Guide,” Federal Emergency Management Agency (FEMA), Report No. FEMA 74, Washington, DC.

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,” Federal Emergency Management Agency, Washington, D.C., (in press).

Filiatrault, A., Uang, C-M., Folz, B., Christopoulos, C. and Gatto, K, 2001, “Reconnaissance Report of the February 28, 2001 Nisqually (Seattle-Olympia) Earthquake,” Structural Systems Research Project Report No. SSRP-2000/15, Department of Structural Engineering, University of California, San Diego, La Jolla, CA, 62 p.

Gates, W.E. and McGavin, G. 1998, “Lessons Learned from the 1994 Northridge Earthquake on the Vulnerability of Nonstructural Systems,” *Proceedings of the Seminar on Seismic Design, Retrofit, and Performance of Nonstructural Components*, ATC 29-1, San Francisco, CA, 93-106.

Juhn, G., Manolis, G.D., Constantinou, M.C., and Reinhorn, A.M., 1992, "Experimental Study of Secondary Systems in Base Isolated Structures,” *ASCE Journal of Structural Engineering*, Vol. 118, No. 8, pp. 2204 2221

Jung, W. Y., 2003, “Seismic Retrofitting Strategies of Semi-rigid Steel Frames Using Polymer Matrix Composite Materials,” Ph.D. Dissertation, University at Buffalo.

Reitherman, R. 1994, “Nonstructural Components,” in John Hall, Editor, Northridge Earthquake: January 17, 1994, Earthquake Engineering Research Institute, Oakland, CA.

Reitherman, R. and Sabol, T. 1995, “Nonstructural Damage,” in John Hall, Editor, Northridge Earthquake of January 17, 1994 Reconnaissance Report, Supplement C to Earthquake Spectra Vol. 11, Earthquake Engineering Research Institute, Oakland, CA.

Soong, T.T., 1990, “Active Structural Control: Theory and Practice,” Longman, London and Wiley, New York

Viti S, Reinhorn A.M., and Whittaker A.S., 2002, “Retrofit of Structures: Strength Reduction with Damping Enhancement”, KEERC-MCEER Joint Seminar on Retrofit Strategies for Critical Facilities, Buffalo, NY

Wolff, E.D. and Constantinou, M.C. 2004, “Experimental Study of Seismic Isolation Systems with Emphasis on Secondary System Response and Verification of Accuracy of Dynamic Response History Analysis Methods”, Report No. MCEER-04-0001, Multidisciplinary Center for Earthquake Engineering Research, Buffalo, NY.