AN OVERVIEW OF NONSTRUCTURAL COMPONENTS RESEARCH AT THREE U.S. EARTHQUAKE ENGINEERING RESEARCH CENTERS

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Abstract

The research programs at the three NSF-funded Earthquake Engineering Research Centers (EERCs) have a focus on nonstructural building components with the broad objective of developing knowledge, assessment tools, analysis and design tools, and fragility data to contribute to efforts underway to prepare guidelines for performance-based earthquake engineering and reduce economic losses in future earthquakes. Summary information on selected research projects at each of the three EERCs is presented in the paper.

Introduction

Nonstructural components of a building are those systems, parts, elements, or components that are not part of the structural load-bearing system but are subjected to the building dynamic environment caused by, for example, an earthquake. Typical examples of nonstructural components include architectural partitions, piping systems, ceilings, building contents, mechanical and electrical equipment, and exterior cladding. Sample data below from Miranda illustrates the typical investment in structural framing, non-structural components and building contents in office, hotel and hospital construction. Clearly the investment in nonstructural components and building contents is far greater than that for structural components and framing.

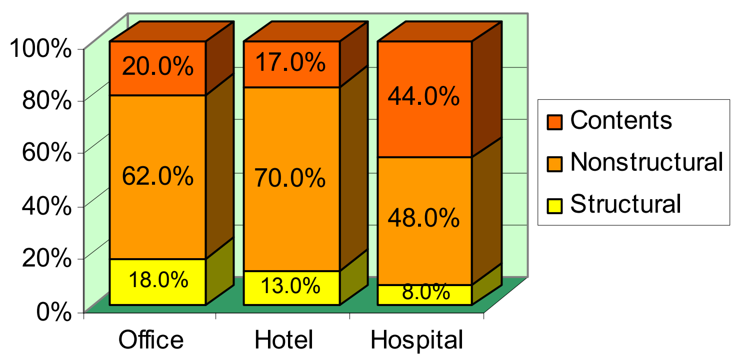

Figure 1. Typical investments in building construction (after E. Miranda)

The importance of nonstructural component issues in seismic design and performance evaluation is now well recognized by researchers as well as practicing engineers. The subject received special attention after the San Fernando earthquake in 1971 when it became clear that damage to nonstructural components not only can result in major economic loss, but also can pose real threat to life safety. For example, an evaluation of various Veterans Administration hospitals following the San Fernando earthquake revealed that many facilities still structurally intact were no longer functional because of loss of essential equipment and supplies.

Economic loss due to seismic nonstructural damage can also be considerable. A case in point is the seismic damage sustained by buildings during the 1994 Northridge earthquake. With the loss of approximately $18.5 billion due to building damage, nonstructural damage accounted for about 50% of this total (Kircher, 2003).

As a result of past earthquake losses and the level of investment in nonstructural components and contents, considerable attention has been paid in recent years to this subject area to develop a better understanding of the seismic behavior of nonstructural components, to realistically assess their seismic vulnerability and performance, and to develop effective rehabilitation strategies. These issues related to nonstructural components have been an integral part of the research programs conducted at the three NSF-funded U.S. Earthquake Engineering Research Centers (EERCs): the Mid-America Earthquake Center (MAE), the Pacific Earthquake Engineering Research Center (PEER), and the Multidisciplinary Center for Earthquake Engineering Research (MCEER). It is the purpose of this paper to briefly summarize the key features of these research activities. Detailed information on many of the research projects identified in this paper is presented in other papers included in the proceedings of the ATC-29-2 seminar.

MAE Center Activities

Some of the MAE projects are summarized below. More information is available at the MAE website: http://mae.ce.uiuc.edu.

Response Modification Applications for Essential Facilities. Nonstructural components figure prominently in this and other MAE projects involving essential facilities. In this project, response modification of unreinforced masonry (URM) buildings, low-rise firehouses in particular, was the focus of investigation. Use of cost effective rehabilitation devices, such as tapered metallic yielding devices (Figure 2), were examined to guard against overall collapse and failure of brittle nonstructural components; aid in protection of occupants and contents; and to ensure continued operation. The passive energy dissipation devices were designed using an energy-based criterion with the objective of maximizing the ratio of the energy dissipated in the devices to the total input seismic energy subject to selected constraints on peak forces and dynamic ductility.

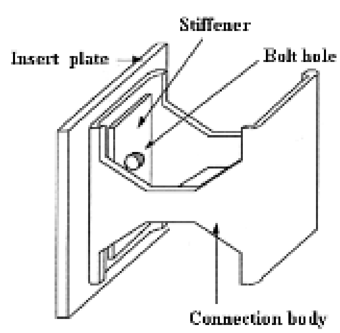

Figure 2. Tapered steel energy dissipation device (after B. Goodno).

Performance Objectives for Essential Facilities. This project examined the behavior of nonstructural components present in essential facilities in mid-America. School buildings were chosen for detailed studies because of the vulnerability of their occupants and the importance of these particular facilities to post earthquake emergency response. Partial height interior unreinforced masonry walls were found in many schools and, because of their clear vulnerability to seismic forces, were selected as the focus of this study. The primary objective of the this investigation was to evaluate and then suggest retrofit strategies for these components to enable them to meet the life-safety and/or immediate occupancy performance levels specified in current FEMA 273 (356) guidelines.

Additional objectives were to assess the accuracy of current evaluation methods recommended by FEMA and, if necessary, to develop improved analysis procedures, rehabilitation guidelines, and performance measures. For example, the V-brace rehabilitation scheme recommended in FEMA 274 to stabilize partial height partitions changes the behavior of the wall in the out-of-plane direction from acceleration-sensitive to both acceleration- and drift-sensitive. An alternative scheme was proposed using a compression stud device (Figure 3) which restricts the behavior of the rehabilitated wall to the acceleration-sensitive region while providing additional lateral capacity through precompression of the wall. Analysis results show that the proposed method can increase the out-of-plane capacity of the wall by up to 30 percent.

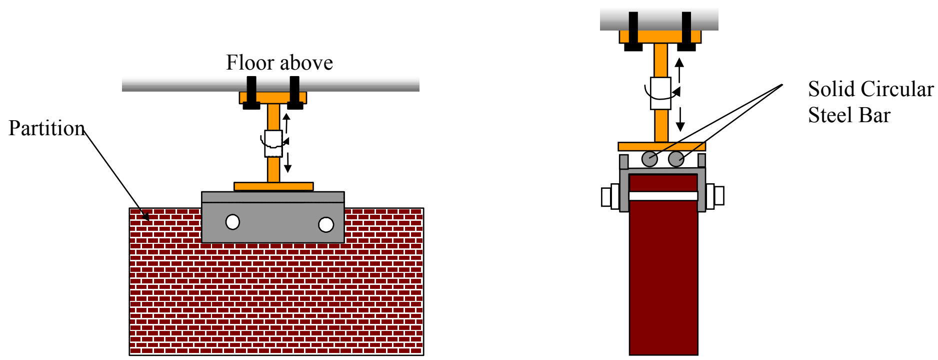

Figure 3. Proposed compression stud device (after B. Goodno).

Regional Interdependent Response. This on-going study will quantify the degree of infrastructure and societal systems interaction under multiple hazards. A major goal of the project is to provide insights on potential methods for determination of consequences and losses due to major seismic events, within interacting systems defined in spatial and temporal domains. Different standard classes of subsystems (e.g., substructures, lifelines, nonstructural components, etc.) are being considered. Examples of interacting subsystems are: (1) lifelines such as highways, railroads, electric power, water supply, gas and oil pipelines; (2) nonstructural components, which include partitions and other architectural elements, piping, electrical and mechanical equipment, and contents; and (3) substructures such as soil and foundation systems.

PEER Center Activities

An objective of the PEER Center is to develop a robust methodology for performance-based earthquake engineering of building structures (Moehle, 2003). The methodology embraces nonstructural components and a significant number of PEER-funded projects are addressing the seismic demand assessment, vulnerability, design and retrofit of nonstructural components. Sample projects include:

- General performance-based framework for structural and nonstructural performance assessment.
- Development of a taxonomy/classification scheme for nonstructural components and fragility development.
- Development of fragility curves for nonstructural components from published literature and earthquake reconnaissance.
- Review of design standards and criteria for nonstructural equipment.
- Testing of nonstructural partition walls.
- Testing of laboratory contents, including heavy equipment and benchtop components.

- Case study on building loss assessment and retrofit related to nonstructural laboratory components.

Some of the PEER projects are summarized below. More information is available at the PEER website: http://peer.berkeley.edu/.

Performance-based Framework and a Taxonomy/Classification System. The damageability of nonstructural components is being addressed in PEER's development of a second-generation performance-based earthquake engineering (PBEE-2) methodology. Part of this effort includes the development of a taxonomic system for defining and categorizing nonstructural building components, and for associating these taxonomic groups with component fragility functions. In PBEE-2, system performance is measured in human, operational, and economic impacts, with the consequence that nonstructural components take on a new relevance. This project will produce a taxonomy for nonstructural components using a scheme related to existing standards such as RS Means' assembly-numbering system. Taxonomic groups will be defined so that, within a taxon, capacity and unit-repair cost can be reasonably assumed to be identically distributed between individual representatives of the group.

Fragility Development. One part of the PEER research program is the development of fragility functions for various types of drift-sensitive and acceleration-sensitive nonstructural components. Three different sources of information are being used to develop these functions: (1) results from experimental research; (2) performance of nonstructural components in previous earthquakes in instrumented buildings; and (3) performance of nonstructural components in previous earthquakes in non-instrumented buildings. A simplified method to estimate acceleration demands in nonstructural components has been developed by Miranda. The simplified procedure is now being used in parametric studies to identify the parameters that primarily affect acceleration demands. Results of the parametric studies will help improve current seismic provisions (such as the *NEHRP Recommended Provisions*) for estimating acceleration demands in nonstructural components. The model is also being used to develop empirical fragility functions of acceleration-sensitive nonstructural components by generating acceleration demands in non-instrumented floor levels of instrumented buildings or in non-instrumented buildings with adjacent free-field recordings. Sample results of the work of Miranda and his research associates are presented in Figure 4, which presents estimates of peak acceleration demands by Miranda and the 1997 *NEHRP Provisions* and measured peak accelerations. The agreement between the measured accelerations and the acceleration estimates of Miranda is excellent.

Damageability and Seismic Protection of Laboratory Contents. A project in this area involved the seismic evaluation of contents of a modern laboratory building: a Science building on the campus of the University of California at Berkeley. The building's contents are typical of a wet laboratory: parallel laboratory benches with shelves above, set against or between walls. Every space is densely packed with equipment (see Figure 5). The contents were surveyed and coded according to their physical characteristics, location, value, hazard potential, and importance to research. A program for seismic restraint of critical objects was developed. Performance of selected contents was tested on shake tables. Designs were completed for the anchoring of critical contents in the existing laboratory building. A key finding from this research is the recognition that seismic protection of many objects in complex buildings such as laboratories or hospitable cannot be accomplished with simplified details.

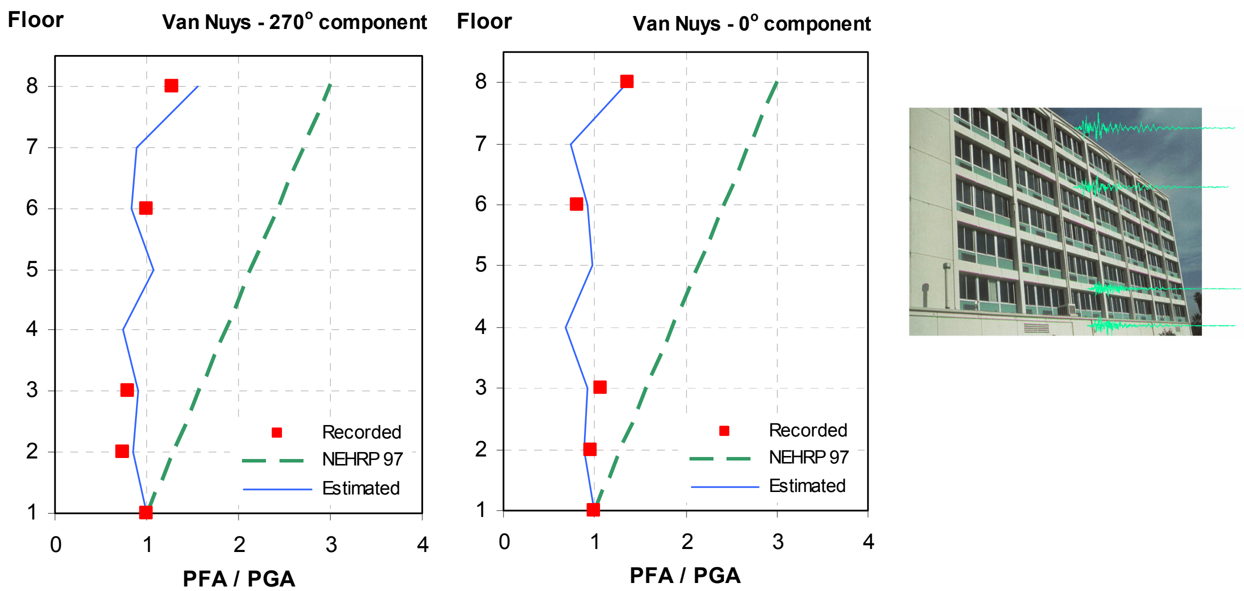

Figure 4. Peak floor acceleration data from measurements, predictions, and 1997 NEHRP Provisions (after E. Miranda)

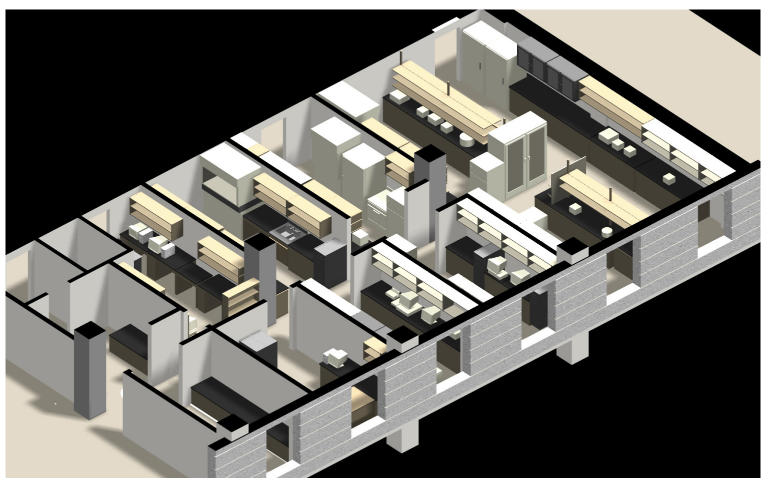

Figure 5. Testbed building on the U.C. Berkeley campus for performance evaluation of nonstructural components (after M. Comerio)

Testing on Nonstructural Partition Walls. The scope of this project is to investigate experimentally the seismic fragility of gypsum light gage metal stud partition walls that are commonly used in modern steel and reinforced concrete office, hotel and laboratory buildings. For this purpose, in-plane shear testing is being conducted on eight different wall specimens. The construction of each specimen follows current standard practice including mudding, taping, and painting of the gypsum finish wallboard. This investigation will culminate in the development of parametric fragility models relating Engineering Demand Parameters (EDP), such as interstory drift, to various Damage Measures (DM), such as cracking patterns. This investigation will serve as a model (or best practice) of how to apply the PEER-PBEE methodology to conduct EDP-DM performance evaluations for other nonstructural building components. Figure 6 shows a sample stud wall being tested at UCSD.

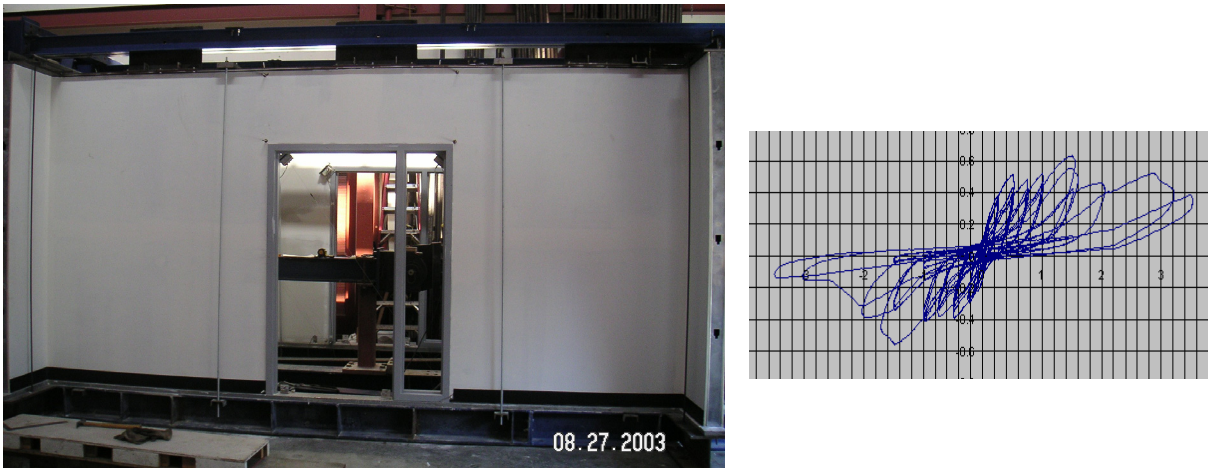

Figure 6. Testing of gypsum board partitions to develop fragility functions (after J. Restrepo and A. Filiatrault)

Testing of Laboratory Contents. A series of earthquake-simulator experiments were recently conducted to study the seismic response of bench and shelf-mounted equipment and contents. Experiments were carried out by constructing a mock-laboratory environment on a bi-axial seismic simulator. The mock-laboratory was constructed with two full height timber walls and two moment resisting frames. Four different integral bench-shelf configurations were assembled with details representative of typical biological and chemical laboratories in science buildings. Transverse and longitudinal bench configurations, using both single and double (back-to-back) benches were constructed. Unistrut support members were used to connect the bench-shelving system to each other and to a concrete floor and timber ceiling system, with details representative of those used in practice. One of the test configurations is shown in Figure 7. For these types of equipment, the preliminary test results indicate that the supporting bench (or shelf) dynamic characteristics play an important role in the overall response of the small rigid equipment. Frequency response functions indicate the integral bench-shelf system may be effectively modeled as a single-degree-of-freedom system.

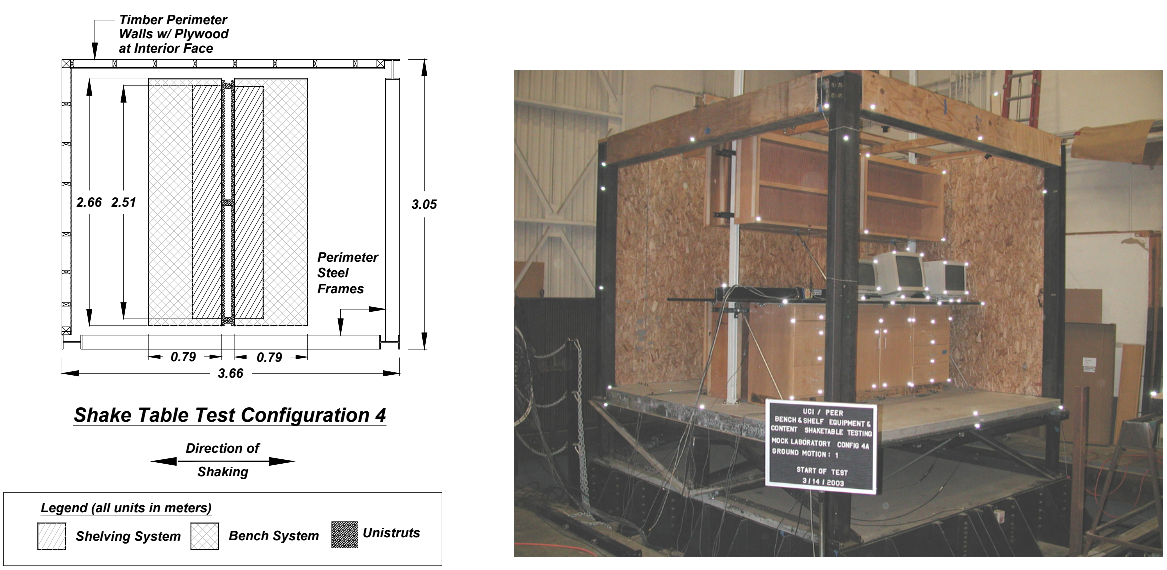

Figure 7. Testing of bench and shelf-mounted equipment (after T. Hutchinson)

MCEER Activities

Research on nonstructural components at MCEER is being conducted within the Acute Care Facilities project. The main objective of this project is to develop engineering and management tools to help enhance the seismic resilience of acute care facilities across the United States. Specific research activities at MCEER related to nonstructural components include:

- Life cycle loss estimation of structural and nonstructural systems.
- Seismic behavior of cable-braced and unbraced welded hospital piping systems.
- Demands on nonstructural components in seismically isolated buildings.
- Assessment of nonstructural components in conventional and protected hospital buildings.
- Fragility assessment of suspended ceiling systems.
- Seismic retrofit of nonstructural components.
- Seismic vulnerability of nonstructural components in East Coast acute care facilities.

Some of the MCEER projects are summarized below. More information is available at the MCEER website: http://mceer.buffalo.edu/.

Life-cycle Loss Estimation of Structural and Nonstructural Systems. Research on life-cycle loss estimation of structural and nonstructural components systems involves seismic hazard description, characterization of structural and nonstructural systems, and definition of limit states for each structural and nonstructural component. Fragility surfaces of the individual components, giving the probability of exceeding specified limit states, are developed by random vibration theory and Monte Carlo simulation. The overall system fragility is calculated from component fragilities by system reliability methods. Figure 8 illustrates a health care facility with a nonstructural system consisting of a water tank and a pipeline and a sample fragility surface for the water tank.

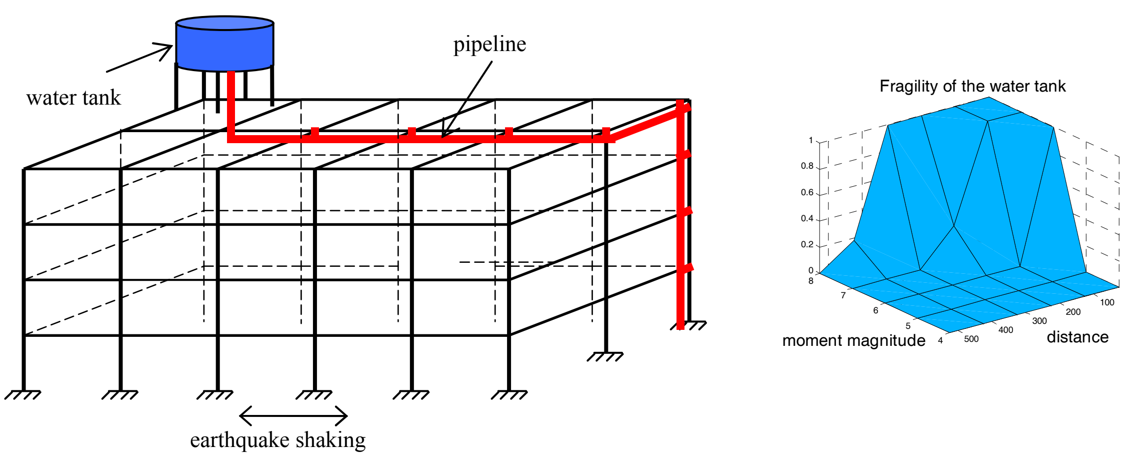

Figure 8. Sample systems for life-cycle loss estimation (after M. Grigoriu)

Seismic Behavior of Cable-braced and Unbraced Welded Hospital Piping Systems. Earthquake simulator studies are being conducted on the seismic behavior of cable-braced and unbraced welded hospital piping systems. The research proposes to identify the capacity of braced and unbraced hospital piping systems and the weak points in typical piping systems. The experimental system is made up of approximately 100’ of 3” and 4” diameter schedule 40 ASTM grade A-53 black steel pipe and includes two water heaters, one simulated heat exchanger, one y-strainer, two check valves and one gate valve. The water heaters and the heat exchanger were anchored to the simulator platform, while the pipes were braced and hung from a stationary frame, which rested on the lab floor, as shown in Figure 9. The system was tested per ICBO AC156. Preliminary results show that the braces limited the displacements, but did not significantly reduce the accelerations of the system. The input motion of 1g was amplified to almost 2.6g at the top of the braced and unbraced piping systems. No significant damage to the piping systems was observed.

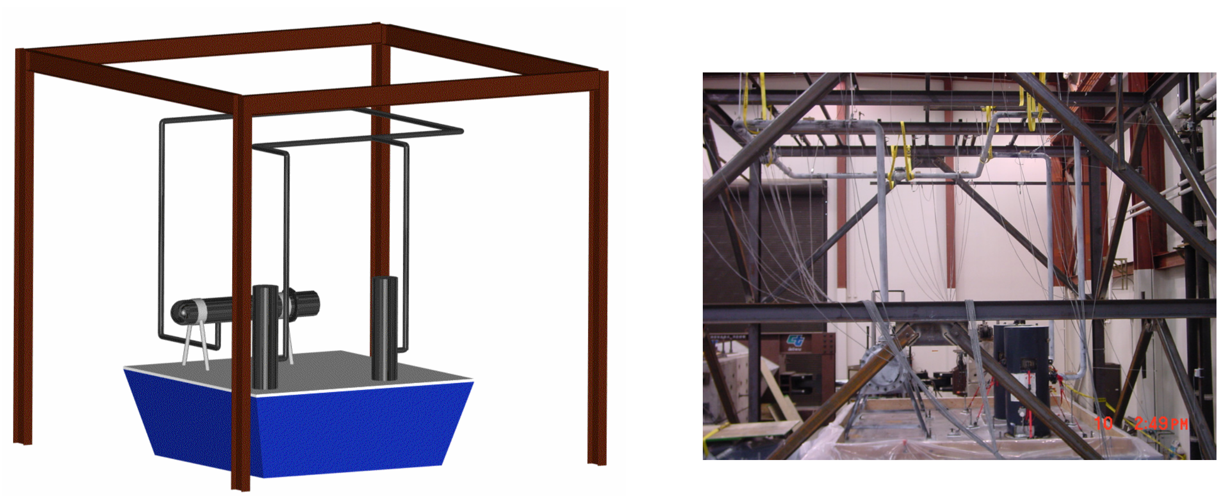

Figure 9. Piping system schematic and photograph of test fixture (after M.Maragakis)

Demands on Nonstructural Components in Seismically Isolated Buildings. An experimental study of the response of seismically isolated buildings with emphasis on the response of nonstructural components is under way. Earthquake simulator tests were performed on a quarter-scale, six story, building model, which was configured as both a flexible moment frame and a stiff braced frame in symmetric and asymmetric configurations. A total of eight different isolation systems were studied, namely, low damping elastomeric bearings with and without linear and nonlinear viscous dampers, Friction Pendulum (FP) bearings with and without linear and nonlinear viscous dampers, lead core elastomeric bearings, and low damping elastomeric bearings in conjunction with flat sliding bearings. Experimental results on primary and secondary system response were obtained, including floor spectral accelerations over a wide frequency range, floor absolute velocities, interstory drifts, and story shear forces. The results of the study provide guidance as to the impact of isolation system choice on the response of flexibly-attached nonstructural components and contents..

Fragility Assessment of Suspended Ceiling Systems. The failure of suspended ceiling systems (SCS) has been one of the most widely reported types of nonstructural damage in past earthquakes. Fragility methods are used to characterize the vulnerability of SCS. Since SCS are not amenable to traditional structural analysis, full-scale experimental testing on an earthquake simulator was performed to obtain fragility data. Figure 10 shows the test fixture and sample fragility data. Several ceiling-system configurations were studied. The results from the full-scale testing are presented as seismic fragility curves. Four limit states of response that cover most of the performance levels described in the codes and guidelines for the seismic performance of nonstructural components were defined using physical definitions of damage. Data was obtained for every limit state to compare the effect of each configuration on the response of the SCS. Based on the results of the experimental testing it was found that (a) the use of retainer clips generally improved the performance of SCS in terms of loss of tiles, (b) including recycled cross-tees in the assemblage of the suspended grid substantially increased the vulnerability of the SCS, (c) undersized (poorly fitted) tiles are substantially more vulnerable than properly fitted (snug) tiles, and (d) including compression posts improves the seismic performance of a SCS.

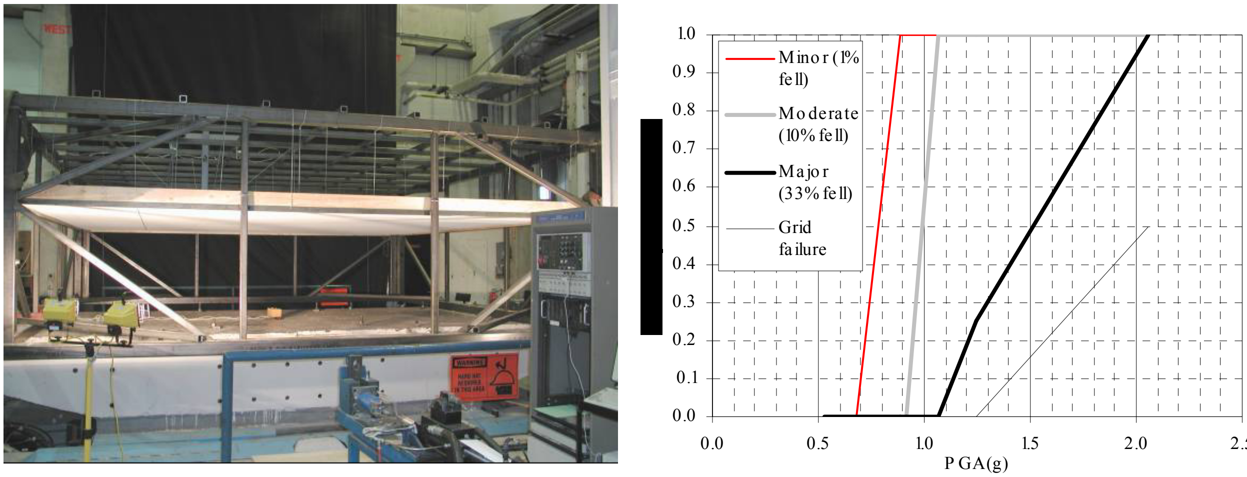

Figure 10. Fragility tests of suspended ceiling systems and sample fragility data (after H. Badillo)

Seismic Retrofit of Nonstructural Components. Seismic vulnerability data can guide the development of improved design and installation guidelines for nonstructural components in critical facilities. In a majority of cases, easy and inexpensive solutions can be found which can significantly reduce the risk of seismic damage to nonstructural components. For example, restraint design for computers and data processing equipment at a data center was recently completed. In this work, an attempt was made to provide a sound basis for designing tethers or cables using site-specific response spectra. The important design parameters were initial angle of cable orientation, initial tension in the cable, and stiffness coefficients of the cables. More complicated nonstructural components might require more advanced retrofit techniques. For example, in the case of rotating machines, there is a dual isolation problem consisting of isolation of housing structures from the machine vibrations and protection of machines during an earthquake to maintain their functionality. The desirable characteristics of machine mounts for the above two purposes can differ significantly due to the difference in the nature of the excitation and in the performance criteria in the two situations. Work is continuing on the development of a semi-active mount that can accommodate different seismic and operational requirements. A functional diagram with a variable damping element for this scheme is shown in Figure 11. This scheme includes a sensor which can detect the start of a seismic event and send ON/OFF signal to a switch in a variable damper and/or spring element which can change the property of the element.

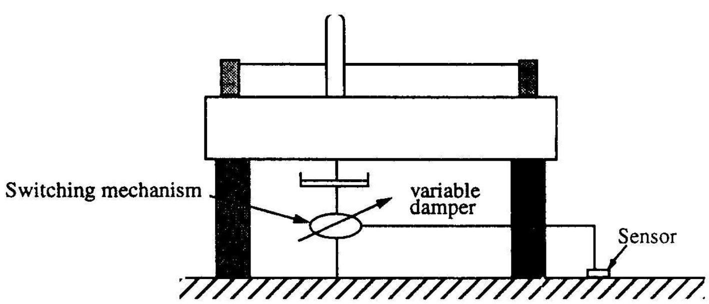

Figure 11. Semi-active mount design for a complex nonstructural component

Seismic Vulnerability Of Nonstructural Components In East Coast Acute Care Facilities. The seismic vulnerability of nonstructural systems in East Coast hospitals is being evaluated through a case study involving a hospital in the State of New York. The vulnerability of selected nonstructural components and systems in the case-study building, including domestic cold water and fire suppression water systems and power distribution systems, is being assessed for two framing-system conditions: the existing late 1960s condition for which earthquake effects were not considered in design, and the proposed retrofit condition for which earthquake effects are considered per the 2000 International Building Code.

Concluding Remarks

Nonstructural components and building contents represent a substantial percentage of the value of most buildings. Much of the economic loss from past earthquakes can be attributed to damage to nonstructural components and contents. In an attempt to characterize and/or reduce damage and loss to nonstructural components and building contents in future earthquakes, each of the three NSF-funded Earthquake Engineering Research Centers (EERCs) is funding basic and applied research on the seismic behavior of nonstructural building components. Tools and knowledge are being developed at the three EERCs to permit evaluation of the vulnerability of typical nonstructural components and contents and reduce the likelihood of damage to nonstructural components and contents in future earthquakes through component- and framing-system-response modification. Such tools and knowledge will be key to the development of robust guidelines for performance-based earthquake engineering: a project termed ATC-58 that is underway currently with funding from the Federal Emergency Management Agency.

Acknowledgements

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