SEISMIC VULNERABILITY AND PROTECTION OF NONSTRUCTURAL COMPONENTS

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Abstract

An area of earthquake disaster mitigation research of growing interest in the U.S. is one of assessing seismic vulnerability and developing mitigation measures for nonstructural components in buildings, particularly critical facilities. This area of research has had limited international collaboration, but has strong potential for broader international involvement.

The research activities in the U.S. in the area of nonstructural components has the broad objective of developing knowledge, assessment tools, analysis and design procedures, fragility data, and protective measures. These activities are designed, in part, to contribute to efforts underway to prepare guidelines for performance-based earthquake engineering and reduce economic losses in future earthquakes. Reported in this presentation are some completed and current work in the nonstructural components area. They address two important technical issues associated with their seismic performance: seismic vulnerability and protection strategies.

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 causes 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. While seismic design of buildings has been well developed and is being continually updated and improved, nonstructural components housed in buildings are rarely designed with the same care or under the same degree of scrutiny as buildings. As a result, buildings that remain structurally sound after a strong earthquake often are rendered unserviceable due to damage to their nonstructural components.

The importance of nonstructural component issues in seismic design and performance evaluation is now better 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). From the viewpoint of economic investment, sample data shown in Figure 1 illustrate typical investment in structural framing, nonstructural 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.

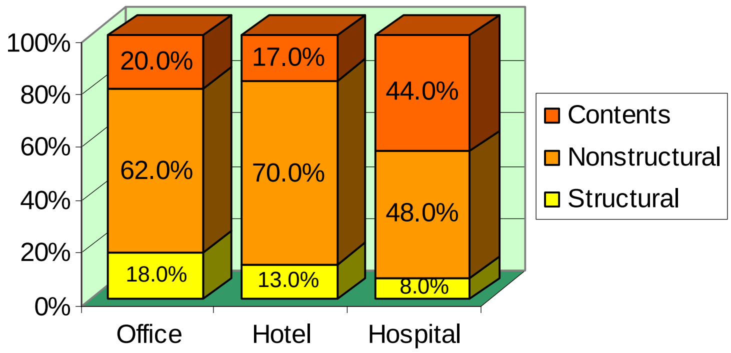

Fig. 1: Typical investments in building construction (after E. Miranda)

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 protection 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. It is the purpose of this paper to briefly summarize the key features of these research activities in the areas of seismic vulnerability and protection strategies related to nonstructural components.

SEISMIC VULNERABILITY

In order to improve seismic performance of nonstructural components and to develop effective protection strategies, seismic vulnerability of these components must be first established. While many approaches can be followed, the development of fragility information for these components can be very useful. Fragility information not only quantify seismic risk for these components under specified site conditions, but also provide information on the effects of key parameters on the fragility results, leading to the development of effective protection strategies.

One approach in developing fragility information for nonstructural components in a systematic way is to first group nonstructural components into the following three main categories:

- Unrestrained nonstructural components
- Restrained nonstructural components
- Nonstructural systems which consist of systems of nonstructural components

Fragility information for the first two groups can be developed analytically and experimentally under a variety of failure modes (e.g., Zhu and Soong, 1998; Chong and Soong, 2000; Lopez Garcia and Soong, 2003a,b). For example, sliding fragility of unrestrained equipment is studied in Chong and Soong (2000) and Lopez Garcia and Soong (2003a,b). Using floor response spectra to characterize excitation inputs, fragility curves such as those shown in Fig. 2 can be determined to allow a quantitative assessment of seismic risks for this class of components under sliding. Specifically, fragility curves in Fig. 2 are obtained when the coefficient of dynamic friction (m_d) is 0.4, the threshold displacement (x_o) is 2 in, and when k varies from 0 to ½, where k is the ratio of the vertical to horizontal component of the peak floor acceleration. Figure 2 shows that a key parameter of interest in this case is k. As k increases, the sliding-related risks increase significantly, which is consistent with damage patterns of nonstructural components that have been observed in recent earthquakes. It underscores the need to consider vertical base motion in seismic vulnerability assessment of unrestrained equipment.

Another significant finding in this study is that the absolution acceleration, thus the inertia force, induced by base excitation at a threshold displacement of the component is relatively insensitive to the base motion but only sensitive to m_d. Surface properties of the component and the base thus become important when impact with neighboring objects become an issue in seismic design.

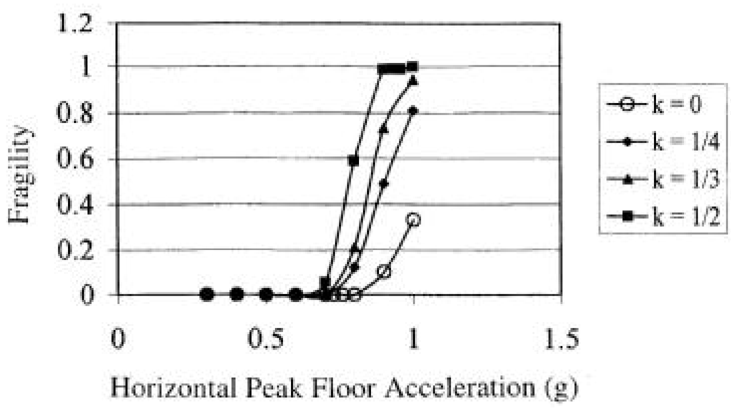

Fig. 2: Fragility curves for m_d = 0.4 and x_o = 2 in

Analytical studies of fragility of some of the restrained nonstructural components have been completed (Lopez Garcia and Soong, 2003a,b). Many stand-alone nonstructural components and medical equipment are anchored or restrained. Some typical restraint schemes are shown in Fig. 3. Two possible failure modes are of primary interest in this case. They are restraint breakage, which generally renders the equipment damaged and nonfunctional, and excessive acceleration levels experienced by the equipment, which causes internal damage to sensitive equipment such as computers, communication and monitoring systems, and medical instruments and equipment.

Figure 4 gives an example of fragility curves obtained when the failure mode is restraint breakage. These results are functions of four parameters: m = coefficient of kinetic friction, T_{eq} = natural frequency of the component in the absence of friction, b = normalized initial restraint tension, and k = ratio of vertical to horizontal peak base accelerations. It can be deduced from these results that (a) fragility is significantly influenced by m, b, and T_{eq}, (b) influence of vertical acceleration coefficient k becomes increasingly important with increasing m regardless of b and T_{eq}, and (c) assuming that fragility curves for $k = 0.75$ are more realistic, fragility curves obtained without considering vertical ground accelerations (i.e., $k = 0$) are always unconservative.

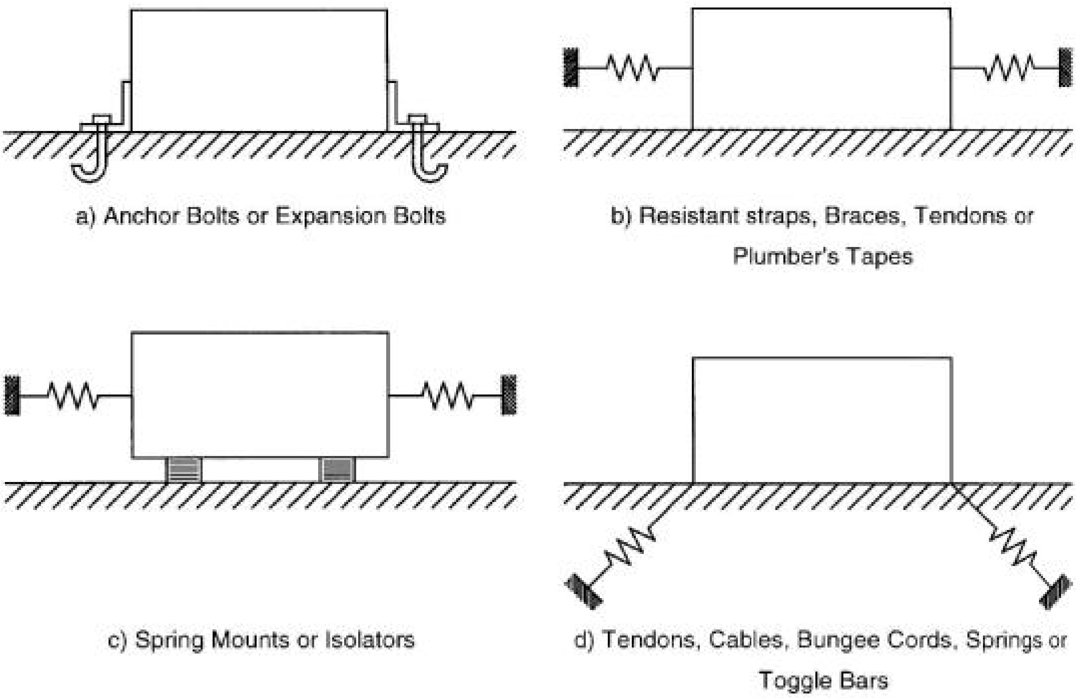

Fig. 3: Equipment with restraints

For the third category in which a nonstructural system consists of many connected individual components, fragility information can be obtained from those of individual components through the construction of a logic tree as illustrated by Fig. 5 for a medical gas supply system (Yao, 1999). Depending on the way in which the components are connected, fragility equations can be established which relate system fragility to the component fragilities. The logic tree approach can also be used for sensitivity analysis to identify critical components of the system, and to determine confidence intervals for the system fragility. For example, Fig. 6 illustrates a healthcare facility with a nonstructural system consisting of a water tank and a pipeline, and a sample fragility surface for the water tank.

PROTECTION STRATEGIES

Clearly, better protection of structures through better design or use of more advanced technologies improves performance of nonstructural components and systems in which they reside. In a recent study (Kircher, 2003), economic losses for non-residential buildings were re-calculated for the 1994 Northridge earthquake region under hypothetical improvement of building performance with a viscous damping system or a base isolation system. Table 1 shows potential savings in direct economic loss using these technologies. As seen in the table, as much as 51% savings can be realized using the damping system technology and 63% savings using the isolation technology.

Improved protection at the nonstructural-component level can also produce significant benefit. In this case, results on seismic vulnerability can guide the development of improved design and protection guidelines for nonstructural components. In a majority of cases, easy and inexpensive solutions can be found which can significantly reduce the risk of seismic damage to nonstructural components (FEMA, 1994). For example, restraint design for computers and data processing equipment at a data center was recently carried out (Meyer et al., 1998). 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. A preliminary design guide was developed and, in general, the following were noted as important considerations:

Table 1: Reduction in direct economic loss through improved building performance of non-residential buildings (adapted from Kircher, 2003)

	Economic Loss (in millions)				
Nonstructural System	As Constructed	With Damping System	% Benefit	With Isolation System	% Benefit
Drift-related	$1,086	$ 407	63	$ 303	72
Acceleration-related	1,952	1,013	48	777	60
Contents/Inventory	2,162	1,124	48	862	60
Total	$5,200	$2,544	51	$1,942	63

- The relative displacement is dramatically increased by steep cable angles, by increases in pre-tension, by reducing the stiffness, and by increasing the equipment weight.
- The optimum angle between the floor slab and the cable can be determined. Increasing the angle causes the equipment acceleration and cable tension to increase significantly compared to decreasing the angle. Accordingly, flattening the cable angle to avoid an obstacle is preferable to steepening the angle.
- Increasing initial tension results in a near equal increase in peak cable tension.
- Doubling friction at the equipment-floor interface causes a 60% increase in acceleration, but has minor effect on displacement and cable tension. Low friction is advantageous for protection of the equipment. This implies that unlocked casters are sometimes helpful.
- Reducing cable stiffness significantly increases displacements, but not accelerations or cable tension.
- Increasing the tributary weight to a cable significantly increases displacements. Accelerations decrease slightly, and cable tension increases modestly.

Direct application of passive energy dissipation systems to nonstructural components and systems have also been studied and proposed. For example, the use of tapered metallic yielding devices (Fig. 7) were examined to guard against overall collapse and failure of brittle nonstructural components in essential facilities. In another study, as an added protective measure, installing a tuned mass damper on the counterweight of an elevator has been suggested for improved elevator performance due to earthquake induced motion (Rildova and Singh, 2003).

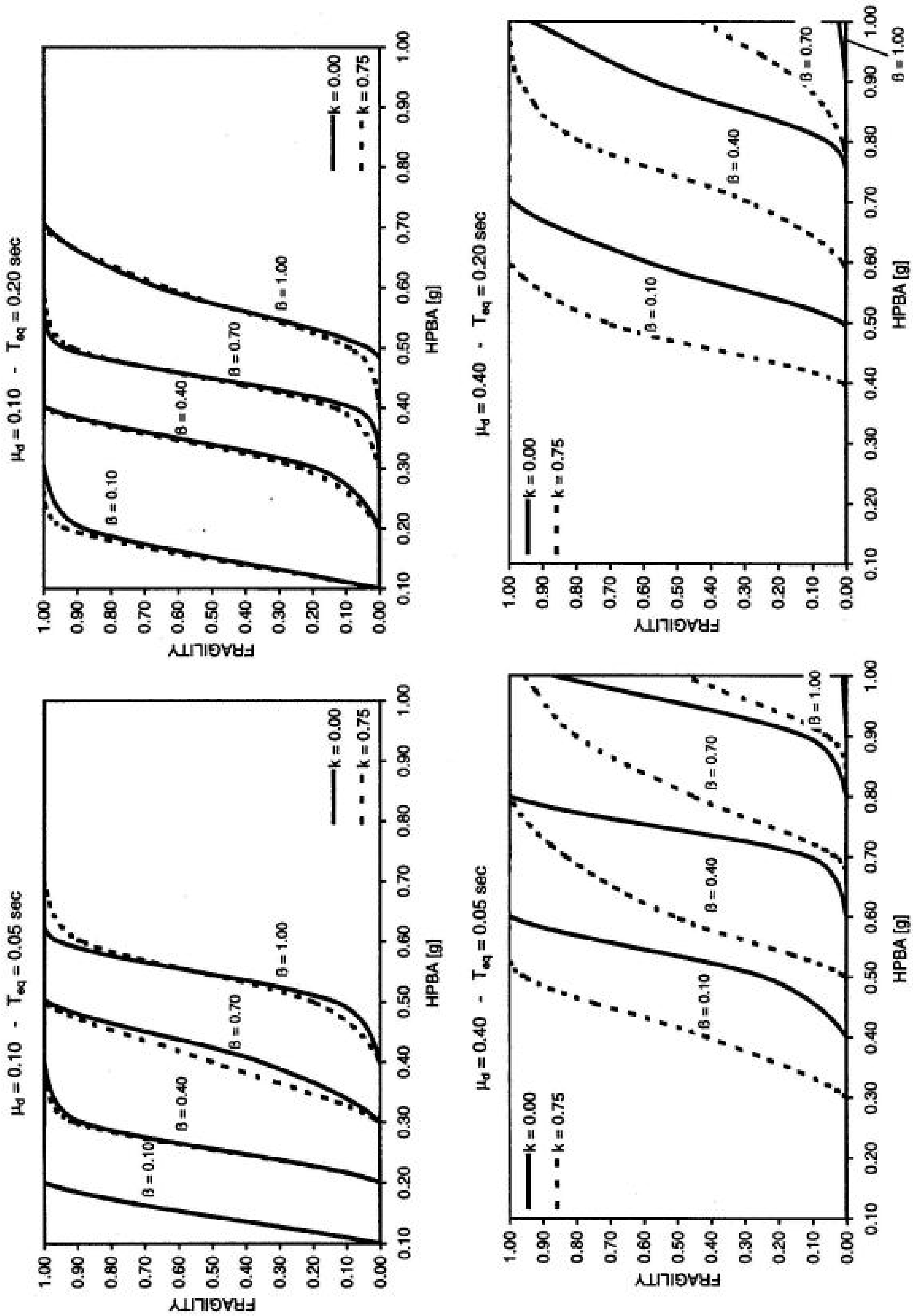

Fig. 4: Fragility curves for restraint breakage limit state (Lopez Garcia and Soong, 2003b)

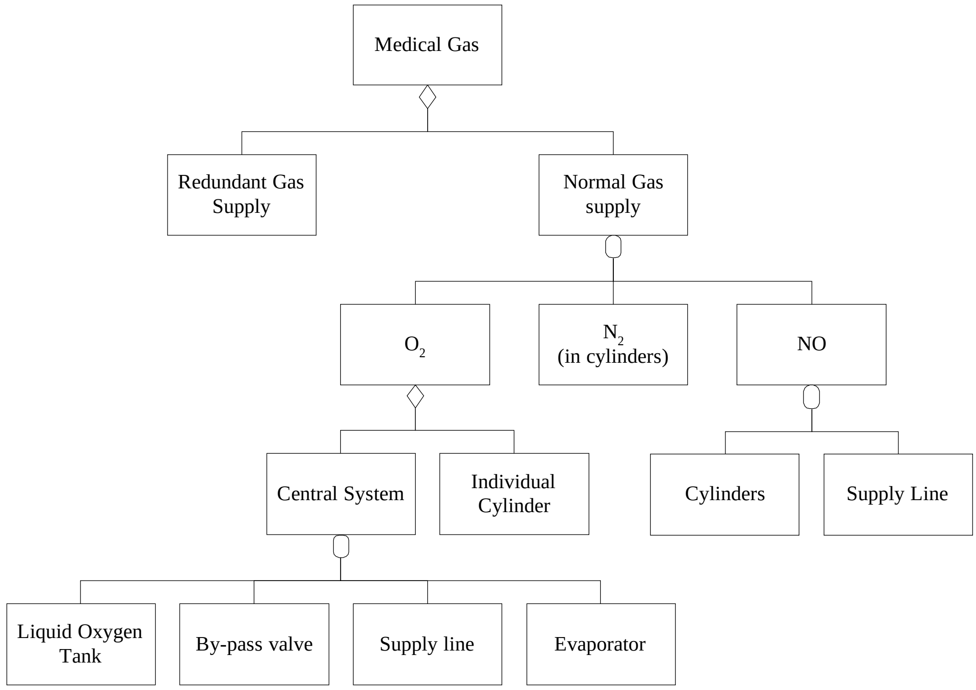

Fig. 5: Logic-tree diagram for a medical gas supply equipment (Yao, 1999)

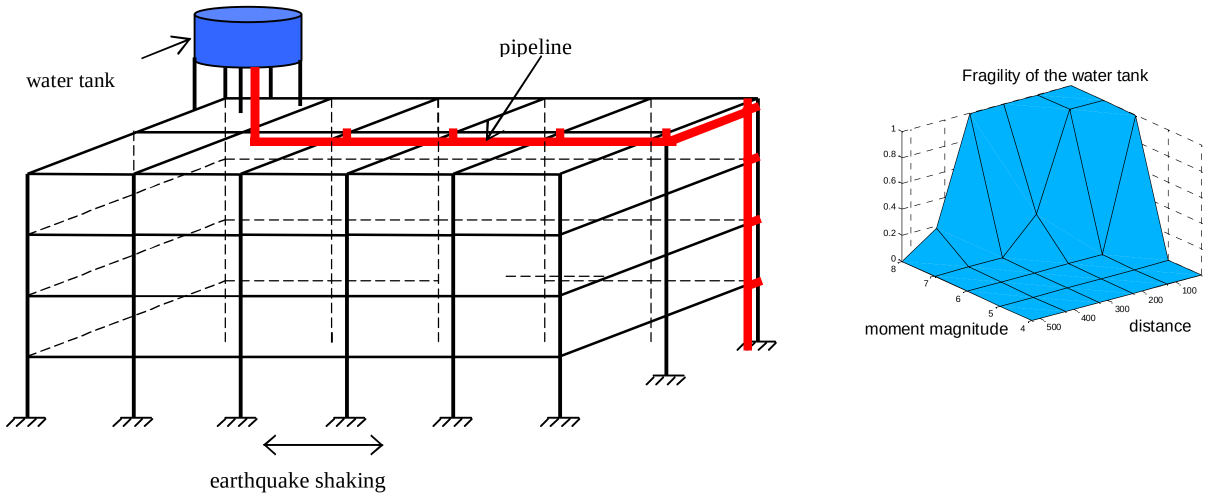

Fig. 6: Sample fragility of a water tank/pipeline nonstructural system (Grigoriu and Kafali, 2003)

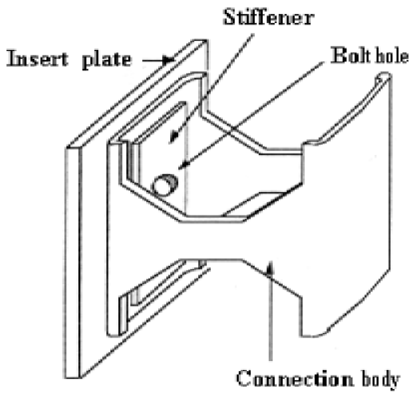

Fig. 7: Tapered energy dissipation device (after B. Goodno)

More complicated nonstructural components may require more advanced protection techniques. For example, in the case of rotating machines, it presents 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. For example, work has been performed on the development of a semi-active mount which can accommodate different seismic and operational requirements (Rana and Soong, 1998). A functional diagram with a variable damping element for this scheme is shown in Fig. 8. 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.

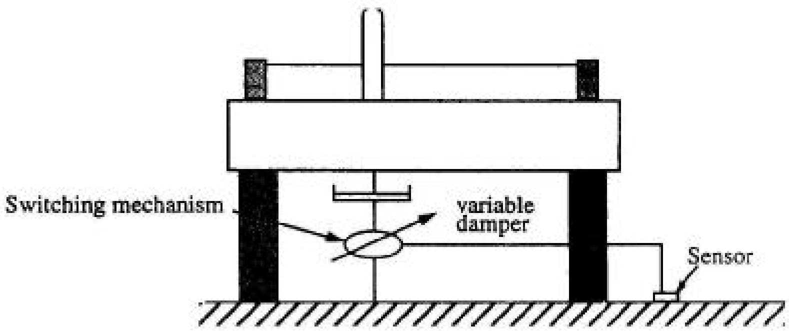

Fig. 8: A semi-active mount design

INTERNATIONAL COLLABORATION AND CONCLUDING REMARKS

Nonstructural damage to critical facilities caused by past earthquakes underscores the importance of addressing the nonstructural issue in seismic design and installation. There is an urgent need to develop stringent seismic design and installation guidelines to insure not only structural integrity, but also functionality of critical facilities, which require protecting nonstructural components, as well as structures, from seismic damage under strong ground shaking.

Recently, efforts are underway in the U.S. to develop a systematic framework for performance-based design of nonstructural components (Bachman et al. 2003). International collaboration on this development is timely and can be highly productive in view of the demonstrated importance of this research effort. This development may involve the following tasks:

Task 1 - Develop a Catalog of Nonstructural Components, Systems and Contents. Identify, organize and catalog the various types of nonstructural components, systems and contents that are vulnerable to loss.

Task 2 - Identify Nonstructural Performance Measures. Identify how nonstructural performance can be characterized or damage measured. These can be loss of functionality, leakage rates, crack widths, breakage, etc.

Task 3 - Identify Engineering Demand Parameters. Review and evaluate input engineering demand parameters (EDP's) that have been proposed. These EDP's may include floor acceleration, drift, ductility demand, cumulative dissipated energy demand, or other similar parameters.

Task 4 - Develop Damage Database. Develop damage database based on available fragility data, publicly available experience data, vendors, and existing test programs. Also, as part of the task, develop a comprehensive electronic master database of building nonstructural components including seismic fragility of the components.

Task 5 - Establish Comprehensive Testing and Certification Protocols. Develop testing protocols, sampling rules, certification testing rules and testing laboratory certification.

Task 6 - Performance Evaluation Case Studies/Testbed Checks. Verify evaluation procedures that have been developed and illustrated how they work through case studies and standardized tests on shaking tables.

For nonstructural components in critical facilities, higher performance levels demand a more rigorous approach to assessing their seismic vulnerability and to developing appropriate protection strategies. This paper has outlined some of these approaches that can be followed in a systematic development of seismic vulnerability methodologies and protection strategies for nonstructural components. A possible work plan for international collaboration is also outlined.

ACKNOWLEDGMENTS

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