Development of a Semi-Active Structural Control System

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Research Objectives

This project seeks to develop a cost-effective semi-active control system for use in buildings and other structures to protect them from destructive earthquake ground motions. By applying a concept of physical parameter modification, the semi-active system is different from active control systems in that its operation does not require a large power source. Yet, the system is more effective in reducing structural response than traditional passive protective systems.

The fundamental research to develop the concept and control principles for the semi-active control system reported in this paper was funded by the National Science Foundation in 1993. Subsequently, the University at Buffalo provided seed money for the development of a small scale demonstration model that validated the principle. The current study is a continuation of the development towards commercialization funded through a Cooperative Agreement with the Office of Naval Research (ONR) as part of a DARPA (Defense Advanced Research Projects Agency), Technology Reinvestment Project (TRP) grant, intended to develop advanced technologies for both defense and civilian utilization. MCEER and the University at Buffalo are members of the ISMIS® Consortium, which includes Enidine Incorporated as the lead organization and Hydro-line, Inc. The Carderock Division, Naval Surface Warfare Center collaborates with the ISMIS Consortium through a CRADA, Creative Research and Development Agreement. The semi-active system under development is based on the idea of real-time structural parameter modification (RSPM) of the system.

The objectives are to develop and commercialize the RSPM technology (or semi-active control system), to improve the seismic performance of structures and to absorb shock in naval applications.

Sponsors

MCEER/NSF
Office of Naval Research through the Technology Reinvestment Project of the Defense Advanced Research Project Agency
Enidine Incorporated
University at Buffalo, State University of New York
National Science Foundation

Collaborative Partners

Enidine Incorporated
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Carderock Division, Naval Surface Warfare Center
Naval Research Laboratory

A number of passive structural vibration reduction technologies (earthquake protective systems) have already been used in structural engineering practice (e.g., base isolation systems and to a lesser extent, fluid dampers). The next frontier of implementing structural control technologies in practice is expected to be the semi-active type. These devices offer the advantages of an active control system but without requiring a large external power source for operation.

Related MCEER Research Activities

- *Hospital Demonstration Project*
- *Rehabilitaion Strategies for Hospital Buildings and Contents,* ***A.J. Aref, M. Bruneau, M.C. Constantinou, G.C. Lee, T.T. Soong****, University at Buffalo,* ***M.P. Singh****, Virginia Polytechnic Institute, and* ***S. Billington*** *and* ***M. Grigoriu****, Cornell University*

This paper describes the recent progress of a special type of semi-active system (also known as a variable passive system) under development at MCEER. This project was initially funded by the National Science Foundation (NSF) through MCEER and the University at Buffalo for developing and proofing the concept. During the past two years, major progress has been made through the ONR/DARPA/TRP Project in partnership with the Carderock Division, Naval Surface Warfare Center, Naval Research Laboratory, Enidine Incorporated and Hydro-line, Inc. This project illustrates how results from a fundamental inquiry supported by NSF was further developed with major funding from mission agencies and industry for commercialization purposes. When fully developed, these devices will be used to protect critical facilities such as hospitals and their contents from damage due to earthquakes.

Introduction

It has always been a major challenge for the structural engineering profession, both in research and practice, to design and construct buildings and other structures to resist forces of nature. Fifty years ago, most engineers performed structural analysis and design based on principles of statics. For dynamic loading such as the forces generated by horizontal ground motions or wind gusts, a structure is designed with a stronger capacity (lateral stiffness) increase in the direction of the expected ground motions.

Since the late 1940s, basic principles of structural dynamics and plasticity theories have been developed, and pseudo-dynamic approaches (mostly based on single degree-of-freedom dynamic models) were introduced in earthquake engineering design. Special emphasis has been given to ductility requirements of structures in the lateral direction.

The current phase of study may be regarded as the development of enabling technology through a systems integrated approach. For defense applications, the product may be regarded as shock absorbers (an intelligent mechanical device) and the primary users would be designers and manufacturers of ships. For earthquake engineering, users would be planners, architects, structural engineers and contractors who are concerned with efficient and cost-effective methods to reduce the seismic responses of new and existing structures.

The immediate next step of the project is to implement a full-scale set of the system in a full-scale, real world structure and to develop specific design guidelines for the technology.

Architects and structural engineers who are challenged to design new structures or to retrofit existing structures to withstand seismic hazards have an increasing choice of devices to use. The supplemental energy dissipation device described in this paper offers another option to the designer.

In the last two decades, a new concept in earthquake engineering design has been advanced: performance-based engineering. At the same time, seismic vibration reduction technologies have been pursued by many researchers. This "structural control technology" is part of a widespread advancement in intelligent mechanical and material systems that are expected to improve the performance of structures in a cost-effective fashion.

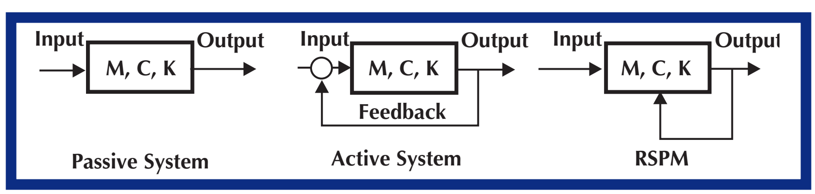
Seismic response reduction technologies are typically classified into the following categories by earthquake engineering researchers:

- Passive Systems
  - Base isolation systems
  - Tuned-mass damper systems
  - Energy dissipation systems
- Active and Hybrid Systems
- Semi-Active (Variable Passive) Systems

To date, a number of passive systems have actually been implemented in buildings and other civil engineering structures. The most popular approach is to use a base isolation system. The tuned-mass damper approach has been used for wind vibration reduction in high-rise buildings, and various energy dissipation systems such as the bracing-type viscoelastic and viscous (fluid) dampers have been implemented in many buildings in recent years. MCEER researchers have been actively engaged in developing various passive and active control technologies since 1986. An MCEER monograph summarizing passive energy dissipation systems has recently been published (see Constantinou et al., 1998).

Most passive seismic protective systems are based on the general idea of increasing the damping of structures (Liang and Lee, 1991). To do this properly, one must consider the structure together with the added device/system in the design process. This may not be a simple task, depending upon the type and configuration of the structure and type of base isolation/energy dissipation systems to be installed. Because ground motions are stochastic in nature and passive systems have only a limited range of effectiveness, active control systems are more efficient. However, except for protecting small or light weight objects, such as equipment, a major breakthrough on how to deliver large active counterforces is needed before widespread use can occur. Active control and hybrid control will remain at the research level with respect to their application to civil engineering structures for some time.

Semi-active systems include smart mechanical and material systems. Through switching or on-off actions, the physical parameters of a dynamic system can be modified in real-time. Because semi-active control systems use passive forces, the authors prefer to use the term variable passive control to contrast the active control that uses active forces. The most comprehensive variable passive system modifies all physical parameters simultaneously and is called real-time structural parameter modification (RSPM) (Lee et al., 1994).



■ Figure 1. Comparison of Passive, Active and Semi-Active (RSPM) Systems

A simple conceptual comparison of the three types of earthquake protective systems is given in Figure 1. It is useful to note that the power

Links to Current Research

- *Current efforts have gone beyond the fundamental research level and are in the midst of developing systems integrated enabling technologies by leveraging major funding from ONR through the Technology Reinvestment Project (TRP) of the Defense Advanced Research Project Agency (DARPA).*
- *The RSPM technology will be applied to the hospital project as an approach to increase the performance of the buildings and to protect the nonstructural components and equipment of the hospital to ensure its acceptable functionality during and after earthquakes.*

supply needed by active control devices is to develop counter forces, which consume the same type of mechanical energy as the external forces. For the RSPM (semi-active) system or any passive system, the power supply is not directly coupled with the mechanical energy of the structure.

Variable Passive Control System

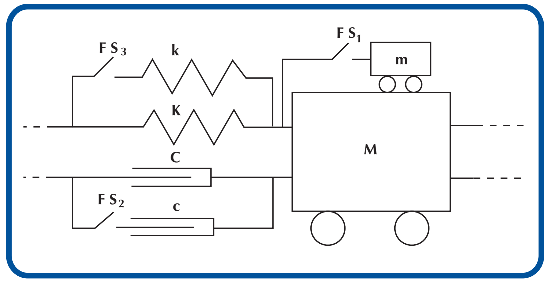
The system under development is referred to as real-time structural parameter modification (RSPM) technology. Although it is regarded as a semi-active system, it evolved from the traditionally defined active control system as an improvement (for not requiring large power supply). In the following discussion of research progress, the term RSPM control technology or ISMIS control technology will be used. ISMIS®, an abbreviation for Intelligent Shock Mitigation and Isolation System, is the registered trademark for Enidine Incorporated's commercial system for naval and civilian applications.

Conceptually, semi-active systems may involve variable damping and/or variable stiffness, as defined by Equations (1) and (2). The RSPM control system is described by Equation (3).

■ Table 1. Development of the ISMIS® Technology

	1st Generation	2nd Generation	3rd Generation
Sensor	Accelerometers Velocity sensors	Accelerometers LVDT Loadcell	Loadcell Pressure sensor
Controller	Analog controller, Electro-magnetic solenoid valve	Digital controller, Servo valve	Analog controller, Electro-magnetic proportional valve
Functional Switch	Length = 6 in Weight = 4 lbs	Length = 38 in Weight = 210 lbs	Length = 38 in Weight = 70 lbs

Note: Length is determined by the application



■ Figure 2. Energy Removal Mechanisms by Using Functional Switches (FS)

- Semi-Active Systems:

$$Mx'' + \underline{C(t)x'} + Kx = F \qquad (1)$$

variable damping, or

$$Mx'' + Cx' + \underline{K(t)x} = F \qquad (2)$$

variable stiffness

- RSPM:

$$[\underline{M(t) + \Delta M}]x'' + [\underline{C(t) + \Delta C}]x' + [\underline{K(t) + \Delta K}]x = F \qquad (3)$$

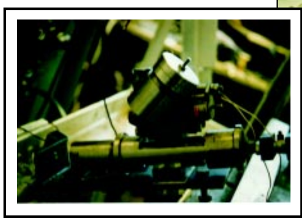
The RSPM system basically consists of three components, the same as those of an active control system. They are: sensors, controllers and functional switches (actuators in the case of active control).

The functional switches are essentially hydraulic devices with the ability to deliver variable stiffness and/or variable damping. They are strategically located in a structure and individually controlled. Obviously, they can be connected/disconnected to mass and to base isolators.

Three typical utilizations of the functional switches are illustrated in Figure 2. In this figure, a functional switch is used to connect/disconnect an auxiliary mass *m* (FS_1), control an auxiliary damper (FS_2), and connect/disconnect auxiliary structural members to control the stiffness of the system (FS_3).

The MCEER project to develop RSPM technology began in 1993 when the basic concept was conceived and the first generation

■ Figure 3 shows the test set up for the first generation system and the corresponding functional switch.



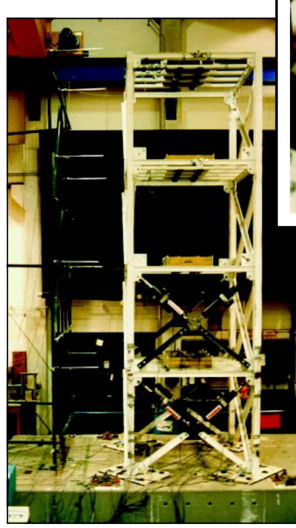
hardware system was manufactured. To date, experimental studies of the third generation system have been completed. This progression is illustrated in Table 1.

For the first generation system, the functional switch was approximately 6 inches long and weighed about four pounds (see Figure 3). That system provided a proof of the concept and a successful application for a U.S. patent (No. 5,526,609) to develop the technology. The second and third generation systems were developed under the ISMIS/TRP program sponsored by ONR and DARPA. The second generation system was developed and tested during 1996-97 (see Figure 4). This proof of concept functional switch used top of the line, commercial off the shelf components to provide the foundation for determining the best specifications for the next generation. These models weighed 200 lbs. The third generation system provided a more streamlined design, reducing the weight to 70 lbs, and was considered to be reasonably proportional to its length. This third generation system was manufactured and tested between 1997 and 1999. Results are summarized in a later section.

Development of Control Devices for RSPM Technology

The first generation system was a small prototype control device. It was a hydraulic device consisting of a plunger seated in a cylinder. An external fluid reservoir was connected to the internal chamber to back-fill it at push-back stage. The reservoir prevents the cavity in the internal chamber, but is only maintained at atmosphere pressure. Thus, the device does not have any reserved stiffness from the pre-pressured fluid. The valve control is realized through an electro-magnetic solenoid. Detailed test data and performance of the device are reported in Liang et al. 1995; 1999.

The second generation of the control device was a servo-valve hydraulic system.The unit operates on high pressure hydraulic power. The device was built to realize high performance with the option to also examine other continuous type control schemes. The study of the control device is reported in Lee et al., 1998a; 1998b.



■ Figure 4 shows the test set up for the second generation system and the corresponding functional switch. The functional switch in this configuration was 38 inches long.

The third generation of the control device was a compact unit with all working parts built internally. The control valve was changed to an electro-magnetic proportional valve that operates on low voltage power. The electronic control circuit was simplified to further shorten the signal delay. Extensive tests of the device on a four story steel structure have been carried out.

Hierarchical Control System

The hierarchical control system is a special feature of the RSPM technology. Four levels of loops are included in the conceptual design. A detailed discussion of these hierarchical control loops can be found in Liang et al., 1995; 1999. The following is a brief summary of their logical connections.

The first level of the hierarchical control, L_1, is a local loop. This loop was realized by employing simple and robust actuation. At present, a control algorithm for this level was created based on variation of stiffness parameters. It was found that the physical parameters under control do not need to be changed very frequently. This led to the development of a switching type of control device, which can tolerate more hostile environments. A local or global sensing system can be used to feed the control unit with the proper control signal. While the switching type of control bears the advantages of being simple, reliable and cost efficient, its limitation is that once the control command has been issued, it cannot reverse the effect. This problem is treated in the second loop.

The second level of the hierarchical control, L_2, is also a local loop. It has been designed to deal with some major side effects associated with switching type of control. The typical scenarios are the signal delay and overdrift due to unbalanced force from a quick change of physical parameters. The delay issue involves many factors, which can become rather complicated. The overdrift often occurs at the time when response frequency is lower than the dominant natural frequency at the local area. This is primarily related to the phase differences between the input excitation and the local output response. Many algorithms have been studied to modify the primary control loop. Some detailed modeling on the signal delay is provided in Lee et al. 1998. Recent improvement of the technology has consisted of a combination of passive damping in the control devices to improve both side effects.

The third level of the hierarchical control, L_3, is a global loop. When the control object is a complicated

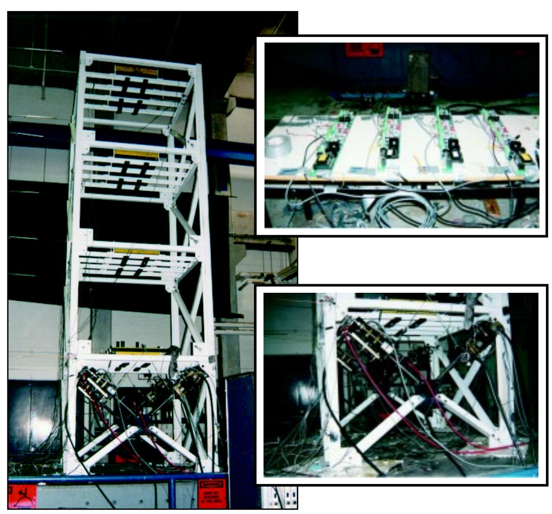


Figure 5. Test Setup for Third Generation System. The four story model is show at left; the top photo shows the control unit; the bottom photo provides a detailed view of the bracing type configuration.

structure, unevenly distributed dynamic characteristics may result in reductions of the overall performance of the control system. By employing a global optimization scheme, the performance may be improved. The global algorithm is still under development at present; the theoretical basis of the control algorithm is minimization of conservative energy (Constantinou et al., 1998, and Liang et al., 1995; 1999). The third level loop will override the first and second loops. However, the global loop control often requires a central processing unit, which adds cost to the entire system.

The fourth level of the hierarchical control, L_4, is a safety loop. The control criteria are established by various safety concerns that are not directly related to the improvement of structural performance. Also, when the control units fails, the actuation device will set, by default, a fail-safe mode.

Experimental Observations

Testing has been an important part of the technology development from the initiation of the project. Back in 1994, a small model structure (see Figure 3) was used to test first generation control devices and verify the system concept (see Liang et al., 1995; 1999). Since 1997, tests have been performed on a new model using the acceleration controlled shaking table, which provides more accurate calibration of the technology.

Many technical specifications of RSPM technology are related to its design dynamic working range. Although the technology is robust and capable of covering a wide dynamic working range, the cost of realizing the desired specification may vary significantly. For instance, the delay restriction for a 2 Hz application is much easier to solve than for 20 Hz. In order to test the RSPM technology for practical seismic applications, it was necessary to include some general structural characteristics in the test vehicle.

Since the majority of building structures requiring supplemental energy dissipation devices are high-rises, a four story moment resistant steel structure was designed for the shaking table tests. The structure is 6 feet (w) x 6 feet (l) x 20 feet (h) with a natural frequency of 2.0 Hz. The dead load is 50 lbs. per square foot, which is similar to that in a real structure.

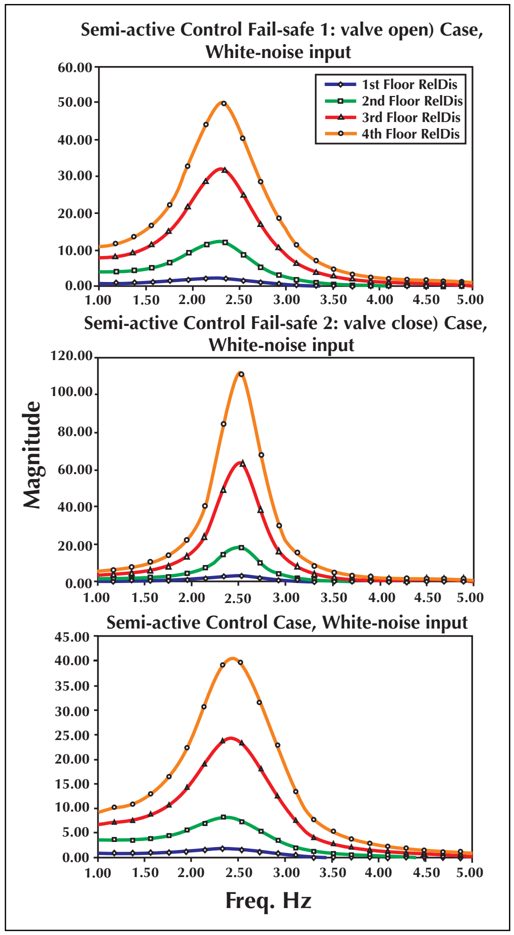


Figure 6. Floor Relative Displacement Frequency Response

The test structure was not intended to be a quarter scale structure in the strict sense. The consideration to abandon the usual similitude approach in the design was due to the following factors:

1. The test results of the technology are more relevant to practical application if the test dynamic working range is the same as the working range of full size devices.
2. The higher frequency problem is more demanding for the response time and often provides

■ Table 2. Kobe Earthquake Peak Response Comparison

Floor Disp.	(inch)	Frame	Passive Damping		High Stiffness		RSPM	
	1st Floor	0.442	0.195	66.9%	0.158	73.2%	0.134	77.3%
	2nd Floor	0.997	0.428	67.8%	0.361	72.8%	0.303	77.2%
	3rd Floor	1.419	0.608	67.9%	0.653	65.5%	0.515	72.8%
	4th Floor	1.672	0.718	67.8%	0.859	61.5%	0.664	70.2%

worse scenarios than lower frequency problems. Therefore, it was desirable to verify the technology at the higher frequency end.

3. The higher frequency prototype device and controller are more expensive.
4. Regular low-rise buildings are not considered to be good candidates for supplemental control devices for cost reasons.
5. Size limitations of the shaking table.

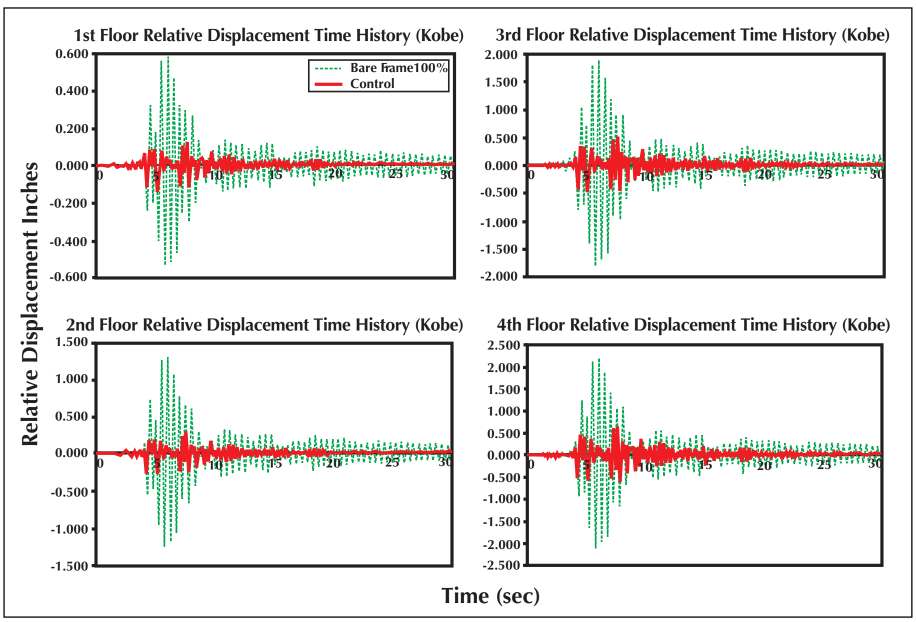
Although the test structure cannot provide all pertinent information about the technology, in particular, information concerning the multi-bay multi-story system, it has provided a basic understanding of the technology at its practical working range.

Test results obtained during 1998-99 are summarized below. The newest generation of the control device has the ability to switch between three states: damping, stiffness and ISMIS control. Each of the three states is compared under different input.

The test setup is illustrated in Figure 5, where the RSPM control devices are diagonally braced on the first and second floors of the four-story structure. Absolute displacement sensors were placed at each of the floors. Accelerometers and strain gages were placed on the floors and at connection areas, respectively.

Figure 6 shows the frequency response function of the three states with the third generation system. It was again verified that the switching scheme was effective when compared to high damping or high stiffness states. The corresponding damping ratios delivered by the three states were 13%, 8% and 14%, respectively.

Table 2 summarizes a set of displacement time history test results. Under 16% Kobe earthquake



■ Figure 7. Relative Displacement Time History With and Without Control

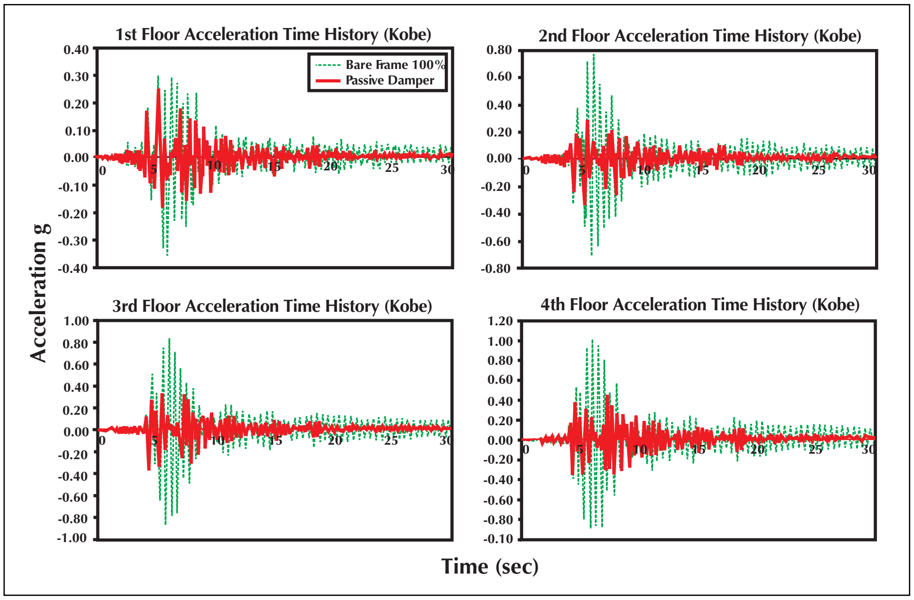


Figure 8. Acceleration Time History With and Without Control

excitation, the original responses of the structure were compared with passive damping, braced stiffness and RSPM control states.

Figure 7 provides the time histories of the displacement response with and without control. Figure 8 provides a comparison of acceleration response of the four floors. Based on a wide range of tests performed on the shaking table, which include white-noise, scaled earthquake records, and modified earthquake records, it was found that the RSPM technology is robust, and outperforms the two passive states in every test case. In particular, the reduction effect is more significant with the large amplitude real earthquake records.

Conclusion and Future Work

An extensive test program has established that ISMIS/RSPM can provide more effective control of story drift than many other passive energy dissipation devices. In particular, testing showed that RSPM is potentially more cost effective than other devices, especially if combined with approaches such as structural bracing or base isolation (Ruan, 1997; and Ruan et al., 1997).

Currently, full scale implementation in a building is being reviewed. This will be one of the two major tasks for the project during 1999-2000. A second major task for 1999-2000 and beyond will be the continued development of guidelines for optimal (or new optimal) RSPM placement in a given structure. This is a rather complex problem but information is needed by the engineering profession dealing with structures (new or retrofit) to be implemented with all types of earthquake protective systems.

The RSPM technology can be applied to other energy dissipation and shock mitigation situations as a mechanical device, with minor modifications (see Lee et al., 1997, and Rasmussen et al., 1997). This is beyond the scope of earthquake engineering.

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