Semi-active control of mid-story isolation building system

Min-Ho Chey [1,*]; J. Geoffrey Chase [2]; John B. Mander [3]; Athol J. Carr [4]

[1] School of Architecture & Art, Yanbian University of Science & Technology, Yanji, Jilin, China
[2] Department of Mechanical Engineering, University of Canterbury, Christchurch, New Zealand
[3] Zachry Department of Civil Engineering, Texas A&M University, TX 77843-3136, U.S.A.
[4] Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand
*Email: hnhdad@yust.edu

ABSTRACT:
This research explores next generation semi-active mid-story isolation building systems for reducing the seismic response of tall structures and mitigating damage. The proposed structural configuration separates the upper stories of a structure to act as the 'tuned' mass semi-actively. This semi-active approach uses a semi-active resetable device for feedback control to alter or manipulate the reaction forces, effectively re-tuning the system depending on the structural response. Simplified two-degree-of freedom (2-DOF) model explores the efficacy of these modified structural control systems and the general validity of the optimal derived parameters is demonstrated. Several cases of the mid-story isolation (MSI) building structures utilizing semi-active resetable devices are described and analyzed. Performance comparisons are based on statistically calculated hysteretic energy and damage demands. The suggested building systems show significant promise for applications of structural control and offers advantages over passive control building systems in the consistent response reductions seen over a broad range of structural natural frequencies. Overall, this research presents a methodology for designing semi-active mid-story isolation (SA-MSI) building systems, highlighting the adaptable structural configuration and the performance obtained. Thus, there is good potential for MSI building systems, especially in retrofit where lack of space constrains some future urban development to expand upward. Finally, the approach presented offers an insight into how rethinking typical solutions with new technology can offer dramatic improvements that might not otherwise be expected or obtainable.

KEYWORDS: Semi-active control; Mid-story isolation; Resetable device; Seismic retrofit; Statistical assessment

1. INTRODUCTION

The control of structural vibrations produced by earthquake or wind loads can be done by various fundamental means. These conceptual approaches include modifying rigidities, masses, damping, or shape, and by providing passive or active counter forces. To date, some methods of structural control have been used successfully and newly proposed methods offer the possibility of extending applications and improving efficiency [1]. It is now established that structural control is an important part of designing important new structures, such as hospitals, and, in some cases, for retrofitting existing structures for earthquake and wind.

As one of the next generation structural control strategy, the basic idea behind the proposed research is to develop a combination of semi-active resetable devices and modified structural isolation systems, and merge them into existing tuned mass damper system concepts. More specifically, to expand effective application of isolation techniques, it is proposed to focus on certain stories of the structure as the main target for isolation. The isolation layer is thus located between separated stories of the structure. Conceptually, it combines emerging semi-active technologies with traditional tuned mass and base isolation concepts to broaden and merge the applicability of all of these approaches to provide improved, more robust performance.

2. TUND MASS DAMPER AND SEISMIC ISOLATION SYSTMES

2.1 Tuned Mass Damper

Tuned Mass Damper (TMD) systems are a practical well accepted strategy in the area of structural control for flexible structures, and particularly for tall buildings [2-5]. It consists of added mass with properly tuned spring and damping elements, providing a frequency-dependent hysteresis that increases damping in the primary structure. The mechanism of suppressing structural vibrations by attaching a TMD to the structure is to transfer the vibration energy of the structure to the TMD and to dissipate the energy in the damper of the TMD. Compared to control devices that are connected to structural elements or joints, the TMD involves a relatively large mass and displacements. The method used to support the mass and provide precise frequency control is an important issue in the design of a TMD. Thus, the ultimate performance of the TMD system is limited by the size of the additional mass, where is typically 0.25~1.0% of the building’s weight in the fundamental mode.

2.2 Base Isolation

Successful base isolation design requires adequate understanding of the influence of each parameter in the isolation system and the superstructure on the overall seismic performance of the isolated building. The primary function of an isolation device is to support the superstructure, while providing a high degree of horizontal flexibility, resulting in a long fundamental period for the isolated building as a rigid mass on the isolator. Skinner et al. [6] demonstrated that the most important feature of seismic isolation is its increasing of the natural period of the structure to achieve this task. Using isolators at the base of building is a still leading approach in the seismic design of structures [7-10]. However, this technique is not applicable in a variety of buildings due to technical difficulties in the isolator technology or in tall structures where overturning is a concern. The high cost of some isolator devices and their implementation in structures are other concerns in designing such systems.

2.3 Mid-Story Isolation (MSI)

Zhou et al. [11] introduced several examples of seismic isolation buildings in China using base isolation, basement isolation and story isolation. One of these examples is the 2-story RC frame platform with plane size of 1,500m wide and 2,000m long that covers the city railway communication hub area. About 50 houses (9-story RC frame) were built on the top floor of the platform. The rubber bearing layer is located on the top floor of the platform to isolate both seismic motion and the vibrations from the railway as shown in Fig. 1. Another practical example of story-isolation structure in China is 8-story office building [12]. The original four-story office building was constructed in the 1950s in Shenyang. A four-story structure with an outer frame has been added to the original building to improve seismic performance of both structures as shown in Fig. 2.

In Japan, Murakami et al. [13] described the design of a multifunctional 14-story building accommodating apartments, office rooms and shops, where a seismic isolation system is installed on the middle story. Furthermore, Sueoka et al. [14] examined a 25-storey building with a mid-story isolation interface between the 11th floor and the 12th floor. The building comprises office space at the upper floors and a hotel space at lower floors. Another retrofitting application using mid-story isolation, a 16-storey personnel-training centre of Taisei Corporation, is presented by Kawamura et al. [15] in Japan. Mid-story isolation was located at the 8th floor, as the building is partially underground from the 7th floor down.

In Korea, meanwhile, there is a recently constructed example of mid-story isolation residential-commercial building [16]. This building consists of 7-story commercial (underground) structure and 35-story parking (1st to 8th floor) & residential (9st to 35th floor) structures. The isolation layer has been added on the top of parking structure as shown in Fig. 4. The lower stories are a typical beam-column framed structure, while the upper stories are a composite structure of flat plate and wall systems.

Fig. 1. Reinforced concrete buildings on top of the platforms in China [11]

Fig. 2. Story-increased structure after construction in China [12]

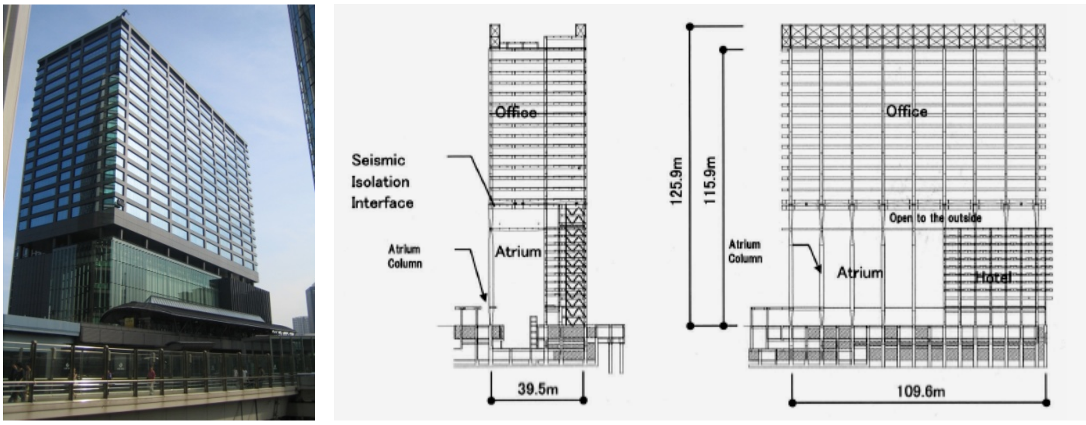


Fig.3. Shiodome Sumitomo building in Japan [14]

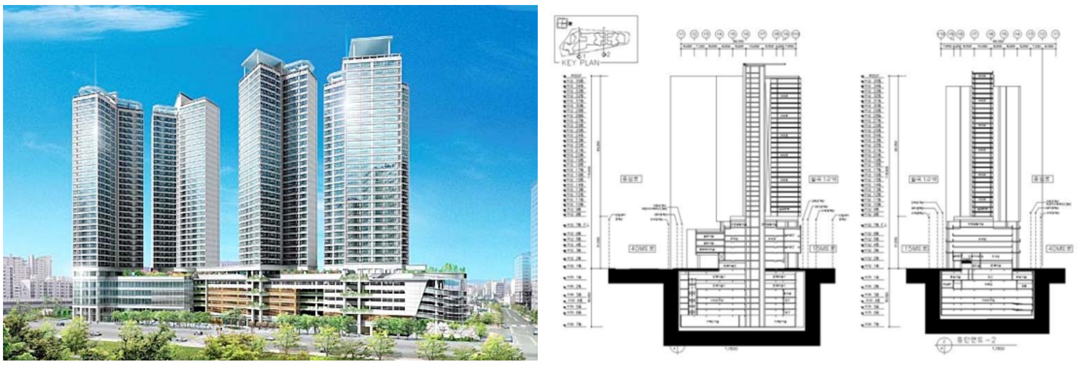
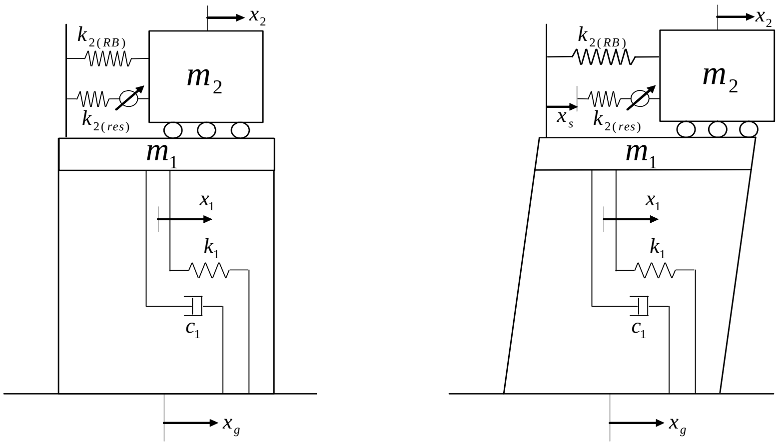


Fig.4. Dong-Il HighVill City building in Korea [16]

3. SA-MSI BUILDING SYSTEM

3.1 Structural Concept

The proposed building system concept can be defined as an extension of the conventional TMD system, but using a large mass ratio. Due to the large mass ratio, the upper portion may experience large displacement. To avoid excessive lateral motion or stroke of the tuned mass, the upper portion can be interconnected by the combined isolation system of rubber bearings and a viscous damper (passive) or a resetable device (semi-active). When the building frame is implemented with the proposed isolation system, the upper portion is supported by rubber bearings attached on the top of the main frame’s columns. The system is shown schematically in Fig. 5.



(a) SA-MIS at rest **(b) SA-MIS at reset**

Fig. 5. SA-MSI building system models for 2-DOF design analyses

The overall mechanism of suppressing structural vibration induced by an earthquake is to transfer the vibration energy of the structure to the isolated upper story. The transferred energy is dissipated at the isolation interface so that seismic force of the entire superstructure can be reduced. Thus, the overall effectiveness depends on the amount of energy transferred or the size of the large tuned mass, and the ability of the isolating elements (viscous damper or resetable device) to dissipate that energy via the relative motions at the interface.

3.2 Resetable Device

Resetable devices act as hydraulic or pneumatic spring elements, resisting displacement in either direction. However, they possess the ability to release the stored spring energy at any time, creating the semi-active aspect of these devices. Therefore, instead of altering the damping of the system directly, resettable devices non-linearly alter the stiffness with the stored energy being released, rather than returned to the structure, as the compressed fluid is allowed to revert to its initial pressure.

The resetable device suggested in this research eliminates the need to rapidly dissipate energy from one side of the device to the other by using a two-chambered design that utilizes each piston side independently. This approach treats each side of the piston as an independent chamber with its own valve and control, as shown in Fig. 6, rather than coupling them with a connecting valve. This approach allows a wider variety of control laws to be imposed, as each valve can be operated independently. Thus, independent control of the pressure on each side of the piston is enabled, allowing a greater diversity of device behaviors [17, 18]. To represent the effects of the resetable device properly, a 'Semi-Active Resetable Actuator Member' has been developed for the inelastic dynamic analysis program, *Ruaumoko* [19].

Fig. 7 represents the hysteretic behavior of simple resetable device where all stored energy is released at the peak of each sine-wave cycle and all other motion is resisted [20]. This form is denoted a "1-4 device" as it provides damping in all quadrants [17, 18].

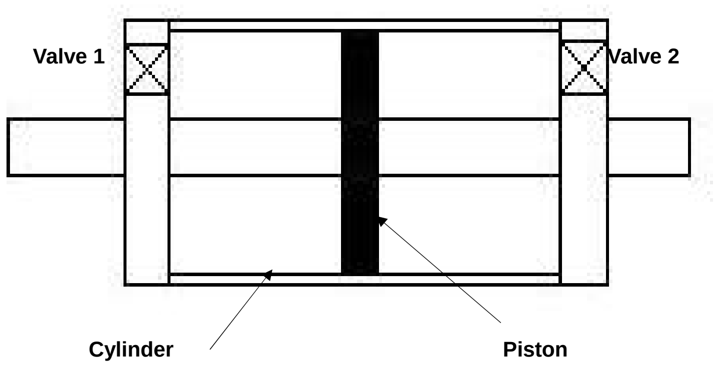


Fig. 6. Schematic of independent chamber design.

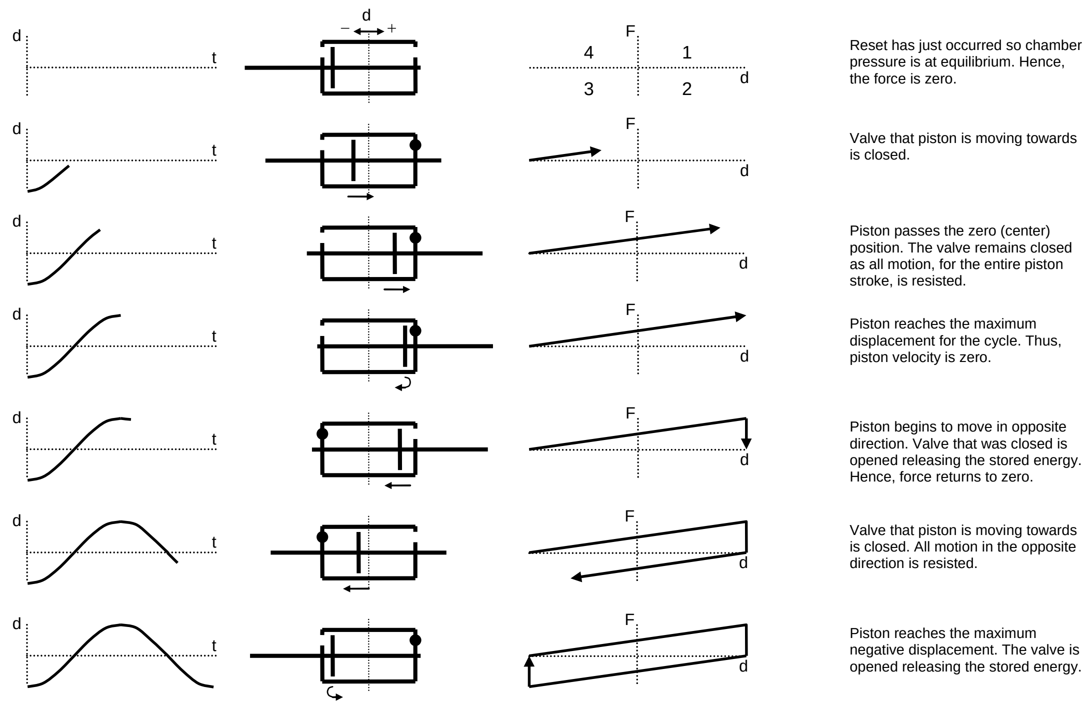


Fig. 7. Schematic showing one cycle of devices [20]

4. 12-STORY MSI BUILDING SYSTEM

4.1. Structural configuration

A 12-story, two-bay reinforced concrete framed structure is used to demonstrate the potential and beneficial effects of TMD building systems [21]. This model was designed originally according to the New Zealand Loadings Code [22] based on the concept of capacity design. For MSI systems, the upper two and four stories are isolated.

The resulting retrofitted structures are thus modeled as '10+2' story and '8+4' story structures, as shown in Fig. 8. Hence, two cases are presented for 12-story MSI building systems, which differ by the mass ratio used as a function of extra stories.

The member sizes adopted in this study are shown in Table 1. The dynamic properties of the uncontrolled 8-story and 10-story frames under the isolation layer, such as the natural frequency, modal effective mass, modal damping ratios, and participation factors, are calculated and listed in Table 2. Fig. 9 shows the schematic description of isolation layer including rubber bearings and viscous damper or resetable device.

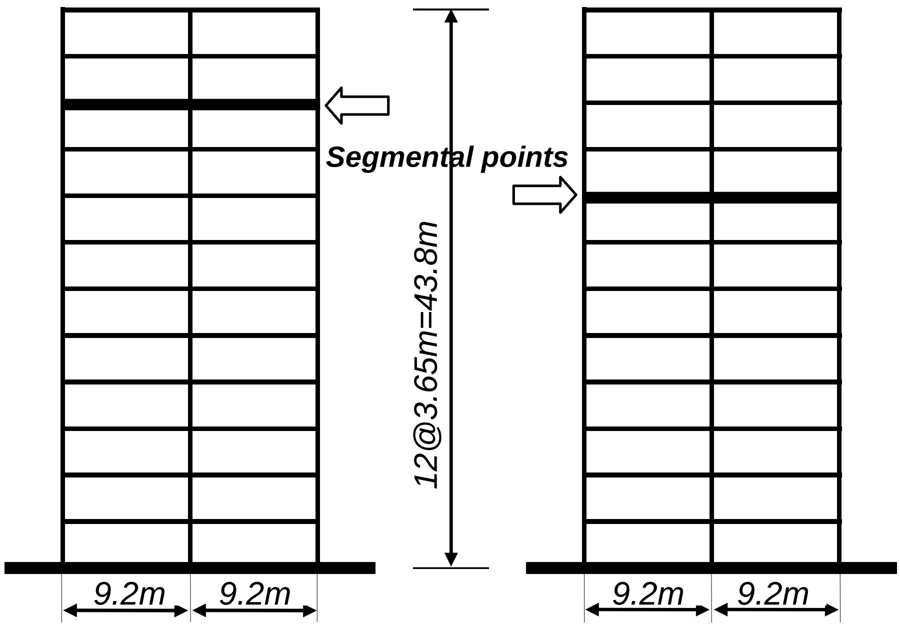


Fig. 8. '10+2' and '8+4' models of 12-story two-bay reinforced concrete frames

Table 1. Member sizes of the frame

Members	Level	Dimensions(mm)
Beams	1 – 6	900 × 400
	7 – 8	850 × 400
	9 – 12	800 × 400
Exterior Columns	1 – 6	775 × 500
	7 – 8	750 × 500
	9 – 12	650 × 500
Interior Column	1 – 6	800 × 800
	7 – 8	725 × 725
	9 – 12	675 × 675

Table 2. Dynamic properties of the frame

Item	8-story	10-story	Unit
Weight	12,940	16,080	kN
1st Modal Mass	1,072	1,301	ton
Natural period	1.187	1.518	sec
Frequency	5.30	4.14	rad/sec
Damping Ratio	0.05	0.05	-
1st Modal Amplitude	1.309	1.343	-

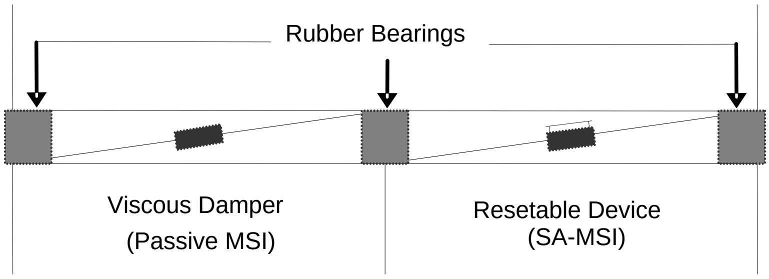
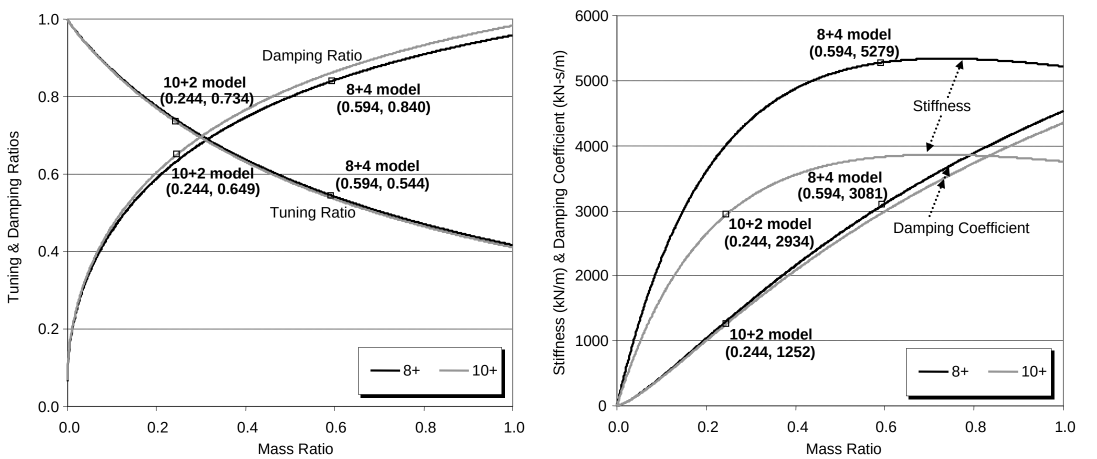


Fig. 9. Schematic description of isolation layer

4.2. Parametric search

Fig. 10(a) shows the optimum damper tuning and damping ratios against mass ratios of 0 to 1 with 5% of internal damping for 10+2 and 8+4 story models. The optimum values for the 10+2 and 8+2 models examined here have been marked by small squares on the lines at the mass ratios of 0.244 and 0.594 respectively. For the 10+2 and 8+4 models, the masses of the primary structures are 1,640t (10-story) and 1,320t (8-story), and the amplitude of the first modal vibration, Φ, of 1.343 and 1.309 are adopted, respectively. Fig. 10(b) shows the optimum damper stiffness and damping coefficient for the models of 10+2 and 8+4 cases. It can be seen that the gaps between the optimum damper stiffness lines for the two models are increased with the increase of mass ratio. However, just small gaps can be found between the optimum damper damping coefficients for the two models.



(a) Damper tuning and damping ratios (b) Damper stiffness and damping coefficient

Fig. 10. Optimum parameters for different mass ratios (10+2 and 8+4 models with 5% of critical internal damping)

5. SESMIC PERFORMANCE RESULTS

5.1. Earthquake suites and statistical methodology

Sommerville et al. [23] developed three suites of 20 earthquake acceleration records to represent the seismic hazard at the SAC Phase II Los Angeles site. The high, medium, and low suites are grouped according to a probability of exceedance of 2%, 10%, and 50% in 50 years, respectively. The low and medium level suites are comprised solely of recorded ground motions pairs, while the high level suites contain five recorded and five artificially generated motion pairs. Each of the ground motion pairs represents the same earthquake measured in orthogonal directions, each of which is at 45 degrees to the fault strike with respect to north, at which the fault plane intersects a horizontal plane.

For the statistical assessments, the response measures are each defined with respect to a single seismic event. To combine these results across the earthquakes in a suite, the following log-normal based statistical tools are employed. To combine the response values of a ground motion suite, a median of the response quantities of a suite with *n* earthquakes is defined and used [24].

5.2. Modal analysis

Modal analysis results using Ruaumoko are shown in Fig. 11. The MSI building systems now offer two major modes of vibration instead of one in the 12-story uncontrolled case. Despite having two major modes and thus a system susceptible to receiving larger amounts of input energy from an earthquake, a relatively large portion of the entrapped energy is concentrated in the isolation layer. For the SA-MSI building systems, the 1st mode dominates the upper stories and a much smaller magnitude 2nd mode dominates the lower story response. Thus, both the 1st and 2nd modes of the original structure are decoupled by the isolation layer.

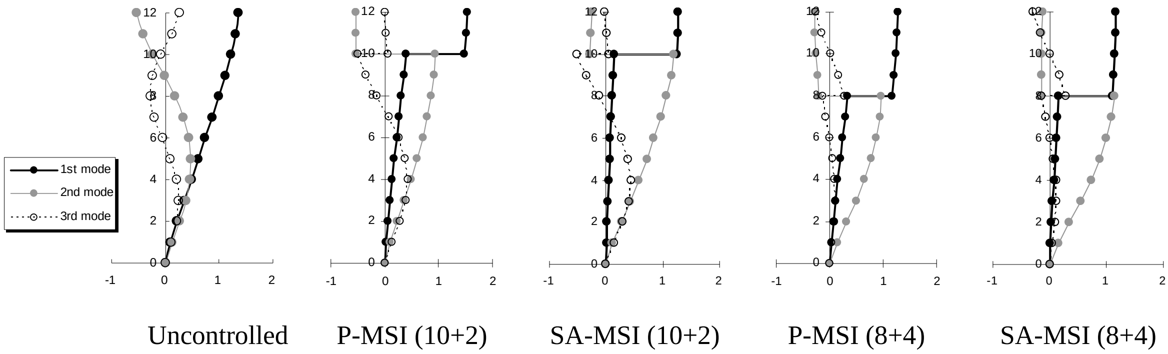


Fig. 11. Mode shapes of ‘10+2’ and ‘8+4’ MSI models

5.3. Time history analysis

While displacement-based index provides a good indication of performance, the resulting information is incomplete as it does not take into account the cumulative damage to the structure. Experimental investigations have demonstrated that structural damage is a function of both peak as well as cumulative values. As hysteretic energy provides a good indication of cumulative damage in structures, 50th percentile values of hysteretic energy are compared for the MSI systems for each set of ground motions.

The hysteretic energy dissipated by the frame members at each floor along the height of the structures are developed in Fig. 12. As expected, the amount of hysteretic energy dissipated by the structure members increases. The comparison of this figure shows that the higher level of hazard produces high energy demands in the lower stories. In particular, clearly lower energy demands at upper stories which are above the isolation layer can be found due to its interception of the energy flow up from the base. This structural property produces the reduced energy demands of the lower stories too. In other words, the amount of transferred energies from the base was decreased by splitting the lump of overall structural mass and, therefore, the dissipated energy along the height is reduced. In the low suite of motions, the energy curves of the isolated upper structures lie along the y-axis, as they are successful in isolating and maintaining the upper structure within the limits of elastic behavior. In the medium and high suites of motions, the MSI systems are still successful at keeping the response essentially linear, as indicated by very low values of hysteretic energy indices.

Finally, as a representative energy value, all of the dissipated energy values along the height are summed to establish a total structural hysteretic dissipated energy index, as seen in Fig.13. Again, the control effects are shown to become significant for the larger mass ratio (8+4) and the SA-MSI system, and the control effectiveness difference is pronounced from the P-MSI(10+2) to the SA-MSI(8+4) systems. This result shows that the combined operation of the semi-active device and large tuned mass contributes greatly to the effectiveness of the overall MSI control system compared to typical and optimal passive design. Overall, all the MSI systems were successful in reducing the seismic hysteretic energy demands at all hazard levels.

The distribution of story damage indices are shown in Fig. 14. Story damage indices are based on the member damage indices in a level. It can be said that the distribution of story damage has a similar pattern to that of story dissipated energy, which is used as a weighting factor for the calculation of the damage index. The only difference between these two indices is from the part of structural deformation. From the figure it can be seen that all of the MSI systems suffer insignificant repairable story damage. The figure also shows that the damage indices of the upper isolated stories for every suite are less than 0.4 at each level, which indicates again the effective interception of energy flow at the isolation layer. Overall, it seems that the main benefits of the reduced damage demands are on the upper stories for each suite, rather than for the lower stories.

The structural damage indices, which indicate the damage of the whole structure, are summarized in Fig. 15. The structural damage indices are obtained as a weighted average of the local damage at the ends of each element, with the dissipated energy as the weighting function. The structural damage indices for all suites are less than 0.5 except. Hence, all of the MSI systems are repairable for those suites. Overall, he SA-MSI(8+4) system proves to be more effective than P-MSI system in terms of structural damage indices and this effectiveness becomes more pronounced for the lower hazard suites.

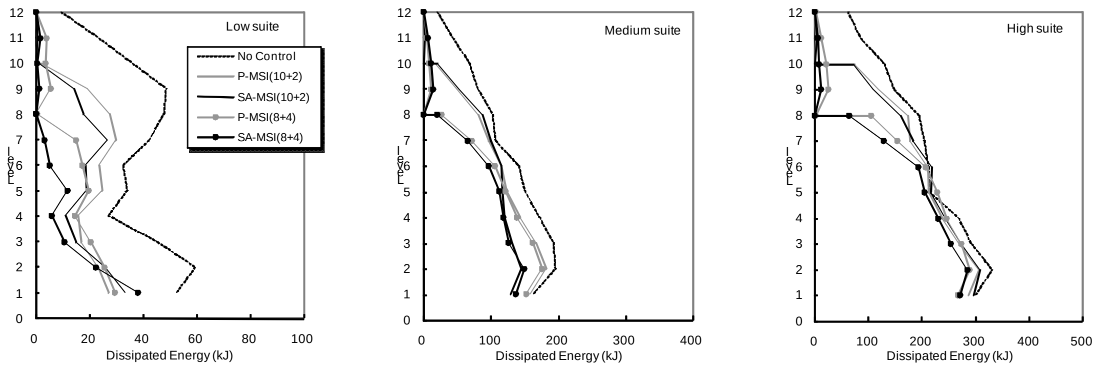


Fig. 12. Story dissipated energy (50th Percentile / Low, Medium and High suites)

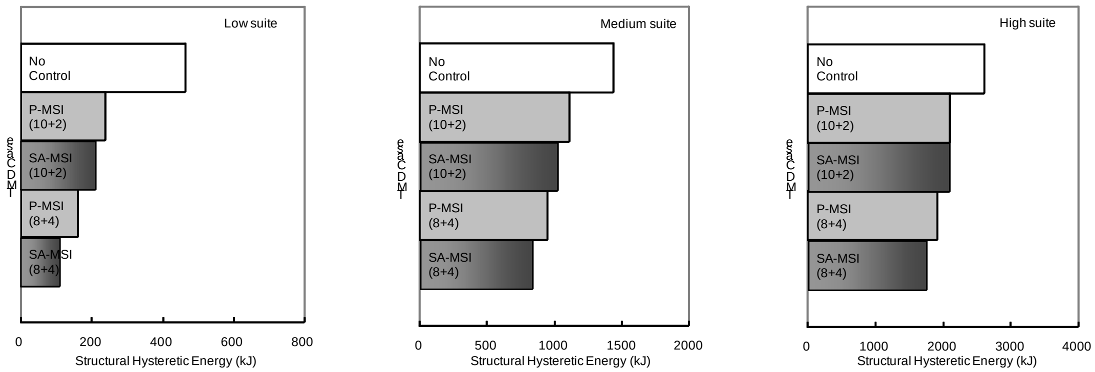


Fig. 13. Structural dissipated energy (50th Percentile / Low, Medium and High suites)

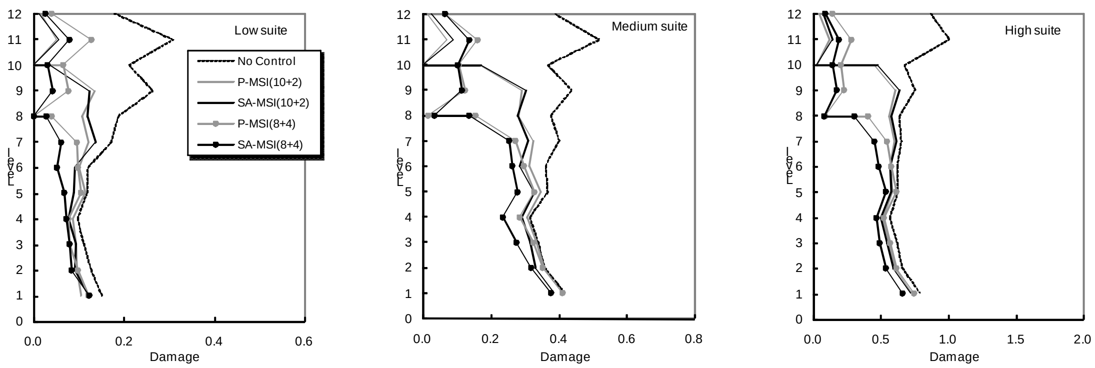


Fig. 14. Story damage (50th Percentile / Low, Medium and High suites)

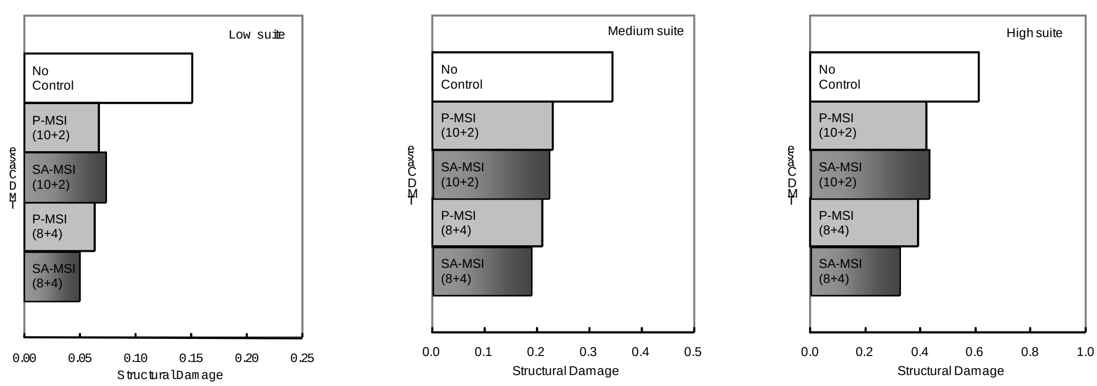


Fig. 15. Structural damage (50th Percentile / Low, Medium and High suites)

6. CONCLUSIONS

Structural control provides an extra mechanism to improve seismic structural performance. For maximum effectiveness, minimal control effort is required to achieve the desired performance goals. Based on this point of view, this research has demonstrated the validity of the realistic MSI building systems for consideration in future design and construction.

The details and results of a set of comparative studies are used to assess the feasibility and effectiveness of such isolation systems. From the results of this comparative study, it is found that the proposed scheme may significantly reduce the seismic response of a structure, even if the structure is nonlinear. In view of these findings, and the fact that they might be relatively easy to construct using these emerging SA devices, it is concluded that the proposed SA-MSI building system has the potential to become a practical and effective way to reduce earthquake damage. Thus, these systems merit further studies to examine their advantages and to further develop experimental validation and design solutions, leading eventually to practical initial designs.

The development of designs suitable for implementing SA-MSI energy management systems ensure the proposed research remains focused on outcomes that are immediately useful. All such outcomes will advance the state of the art by providing additional knowledge and capability from which structural designers can draw in developing new structures or retrofitting existing structures.

Further improvement of the SA-MSI techniques presented requires detailed investigation on the stability margin of flexible frames. Additional study is also required on the passive and semi-active combined control system, to improve the performance of this technique in reducing earthquake effects in a variety of buildings. Future structural control research, particularly using resetable devices, should begin from the base point of optimizing the control system to the demands of each individual structural system considered.

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