Innovative Seismic Retrofitting Strategy of Added Stories Isolation System Utilizing Optimal Tuned Mass Damper Principle

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Innovative Seismic Retrofitting Strategy of Added Stories Isolation System Utilizing Optimal Tuned Mass Damper Principle

(Running Title: Added Stories Isolation System)

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Abstract

The seismic performance of 'Added Stories Isolation' (ASI) systems are investigated for 12-story moment resisting frames. The newly added and isolated upper stories on the top of the existing structure are rolled to act as a large tuned mass damper (TMD) to overcome the limitation of the size of tuned mass, resulting to '12+2' and '12+4' stories building configurations. The isolation layer, as a core design strategy, is optimally designed based on optimal TMD design principle, entailing the insertion of passive flexible laminated rubber bearings to segregate two or four upper stories from a conventionally constructed lower superstructure system. Statistical performance metrics are presented for 30 earthquake records from the 3 suites of the SAC project. Time history analyses are used to compute various response performances and reduction factors across a wide range of seismic hazard intensities. Results show that ASI systems can effectively manage seismic response for multi-degree-of freedom (MDOF) systems across a broader range of ground motions without requiring burdensome extra mass. Specific results include the identification of differences in the number of added story by which the suggested isolation systems remove energy.

Keywords: added stories, seismic isolation, tuned mass damper, parametric optimization, statistical method

1 Introduction

Based upon new and emerging findings in the area of seismic effects on buildings, an increasing number of existing structures are facing the necessity of seismic retrofit. There is not yet a practical method for a large number of buildings to improve their performances in the case of an earthquake event. In addition, there is an increasing desire to expand upwards due to lack of new land to develop. The tuned mass damper (TMD) system can be a great help for both cases because it does not require any major changes in existing buildings and, in some cases can be applied without significant interruption in their operation. TMDs of all possible types have the added advantage of being effective and feasible for taller structures where base isolation is not possible. However, the ultimate performance of the TMD system is limited mainly by the size of the additional mass, which is typically 0.25~1.0% of the building's weight in the fundamental mode.

In an attempt to overcome the limitation of TMD size and find the reliable use of large sized TMD, several studies have been performed by considering a certain part of the structure itself as a tuned mass [1-3]. These seismic isolation strategies using TMD design principle have been extended to convert a structural system, especially a high-rise structural system, into a modified TMD system. Other researchers, furthermore, suggested some modified structural configurations consisting of intentionally isolated structural components utilizing the proper interaction between the segregated structural portions [4-7]. In their studies, they obtain a result that the seismic force to the structure may be reduced by concentrating seismic energy dissipation in the isolation interfaces. They also found that the response of the structure is affected by high frequency modes according to the vibration features between the segregated structural portions.

In an ideal case for the retrofitting of existing structures, it is possible to apply this technique on top of the existing structure simply by adding a few stories as these stories become part of the structure control system, alleviating the necessity for additional mass that is redundant for the majority of the time. This approach is considered as a quite lucrative retrofit approach in places where land for new buildings is expensive. In this study, a comparison between a 12-story (original target structure) model, 14-story and 16-story (retrofitted structure) models including 'Added Stories Isolation' (ASI) system are performed. These retrofitted cases can be interpreted as adding two or four more stories on top of the existing 12-story structure, and it is intended to provide the background to bridge the gap between conventional structural design and the emerging field of structural control that actively manages structural response as it occurs.

The objective of this study is to take the extended concept of TMD principle to the stage of feasible, practical implementation of ASI system to create large capacity energy management systems and its statistical response verification for existing structures without requiring burdensome extra mass or large power sources.

2 Prototype Structural Modeling

A prototype 12-story reinforced concrete framed structure, which was designed originally by Jury [8], is introduced to demonstrate the potential and beneficial effects of the ASI systems as shown in Fig. 1(left). More specifically, as a target structure, it was designed according to the New Zealand Loadings Code [9] based on the concept of capacity design. This structure was revised several times following the requests of the structural upgrades and code revision [10-12]. This model is strong but close to the current practical design requirements. The building dimensions and member sizes adopted in this study are shown in Fig. 1 and Table 1.

In dynamic analysis, it is important to set up a proper mathematical model that reduces the gap between the analytical results and the true behavior of structure during an earthquake. Thus, the detailed dynamic modal properties of the frame have been presented, along with the mathematical modeling and computational method (Table 2). Overall, it is a realistic nonlinear structure that is broadly representative of tall framed structures internationally. It was noted that under the considered structural properties and ground excitations, the displacement response due to the first mode constitutes approximately 80% ~ 90% of the total displacement response. Thus, the first mode was selected for the design of the ASI systems considered. The modeling technique associated with this model has been developed by the inelastic time-history analysis program, RUAUMOKO [13].

For the suggested ASI systems, two stories and four stories are respectively added and isolated for the control of 12-story models and these mean that 24% and 40% more masses are added to the 12-story structure creating ‘12+2’ and ‘12+4’ story structures, respectively. These retrofitting cases are shown schematically in Fig. 1 (center and right).

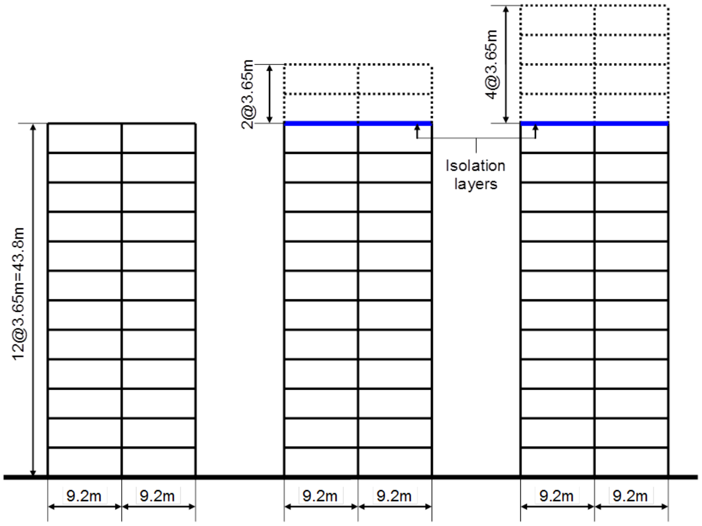


Fig. 1 12-story target model (left), 14-story and 16-story retrofitted models (center and right)

Table 1 Member sizes of the framed structures (Target and retrofitted)

Members	Level	Dimensions (mm)
Beams	1 – 6	900 × 400
	7 – 8	850 × 400
	9–16	800 × 400
Exterior Columns	1 – 6	775 × 500
	7 – 8	750 × 500
	9–16	650 × 500
Interior Column	1 – 6	800 × 800
	7 – 8	725 × 725
	9–16	675 × 675

Table 2 Dynamic modal properties of the 12-story target structure

(Total weight: 19,190kN; Damping ratio: 5%)

Mode	Mass ($kN\text{-}s^2/m$)	Frequency (rad/sec)	Participation Factor	
			Modal	Mass
1st	1,514	0.53	1.37	0.805
2nd	252	1.52	-0.53	0.134
3rd	74	2.73	-0.27	0.039

In this study, the weights of the structure are converted to masses internally within the program RUAUMOKO. Generally, for building models, masses are typically lumped at the floor levels. These floor masses are then distributed to the different load resisting frames on the basis of the frames tributary areas. The mass used in this study was a lumped mass matrix where contributions are made to the diagonal terms associated with the two translational degrees of freedom at each end of the member, with no mass contribution to the rotational degrees of freedom.

For the modeling of damping, the 'Rayleigh' or 'Proportional' damping model and the initial stiffness matrix was used [13], and 5% critical damping was specified for the 1st and 9th modes of the 12 story framed structure. When the additional stories are placed on the structure, the first mode is affected by the response of the added stories. The previously determined 1st and 9th modal damping values for the structure without the added stories were used for the 2nd and 10th modes with the added stories. Thus, the modal characteristics of the structure without the added stories can be transferred to the structure with the added stories to create a more equal comparison.

3 Optimal design of the isolation layer

3.1 Isolation layer

Fig. 2 shows the schematic description of the isolation layer including rubber bearings and viscous dampers, which are modeled as 'spring member' and 'dashpot member' respectively in the used program RUAUMOKO. The overall mechanism of suppressing structural vibration induced by an earthquake is to transfer the vibration energy of the structure to the isolated added stories. 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 isolated added stories, and the ability of the isolating elements (laminated rubber bearing and viscous damper) to dissipate that energy via the relative motions at the interface.

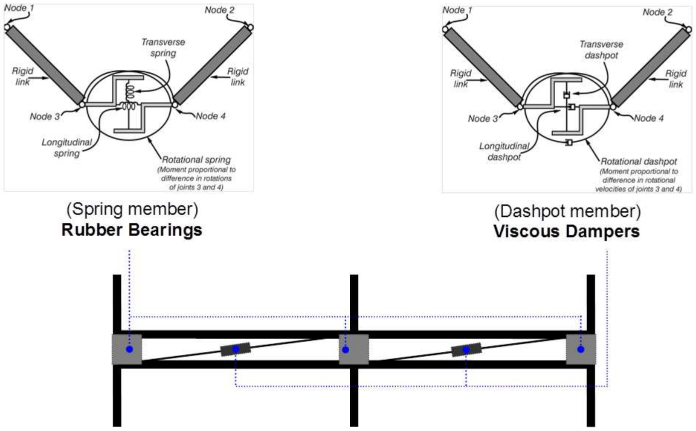


Fig. 2 Details of isolation layer and device members used

3.2 Parametric optimization

While, the basic principles of TMDs on reducing structural response have been well established, optimal TMD configurations are a quite a different problem. In the design of any control device for the suppression of undesirable vibrations, the aim would be to provide optimal damper parameters to maximize its effectiveness. The chief design response oriented parameters of the TMD are its tuning ratio (the ratio of the damper frequency to the natural frequency of the structure) and damping ratio. The other important design parameter is the mass ratio (the ratio of the damper mass to the mass of the structure). Considerable research has been devoted to the study of TMD performance, to enable proper selection of TMD parameters [14-23].

For the optimal TMD parameters, Sadek et al. [24] found that the tuning ratio for a multi-degree-of freedom (MDOF) system was found to be nearly equal to the tuning ratio for a two-degree-of freedom (2-DOF) system for a mass ratio of $\mu\Phi$, where Φ is the amplitude of the first mode of vibration for a unit modal participation factor computed at the location of the TMD. The TMD damping ratio is also found to correspond approximately to the damping ratio computed for a 2-DOF TMD system multiplied by Φ. After suggesting of the parametric design approach to large size TMDs by Sadek et al., several related studies have supported the availability and effectiveness of the use of large TMDs [25-31]. In several studies, the issue of the over-large damping provided by this modified isolation system was addressed and some relative solutions have also been considered [24-27, 31-33].

For convenience, in this study, a flow diagram of optimal design of MDOF ASI system by numerical optimization is used as shown in Fig. 3. For the large mass ratios utilizing in the concept presented, the equations from Sadek et al. [24] are adopted to find the optimal parameters of frequency tuning (f_{2opt}) and damping (ξ_{2opt}) ratios as shown in Eqs (1) and (2) in Fig. 3. Based on these optimal parameters of large TMD, the practical design parameters of k_{2opt} (stiffness coefficient) along with c_{2opt} (damping coefficient) are easily derived as shown in Eqs (3) and (4). From the diagram in Fig. 3, it can be seen that the design is initiated by the amount of added stories, followed by the stage of the parametric optimization for the isolation system suggested. Finally, as a decision making stage, a series of time history analyses using suites of ground motions supplies the individual performance values for the final statistical performance assessment, since the use of a probabilistic format allows for a consideration of structural response over a range of seismic hazards.

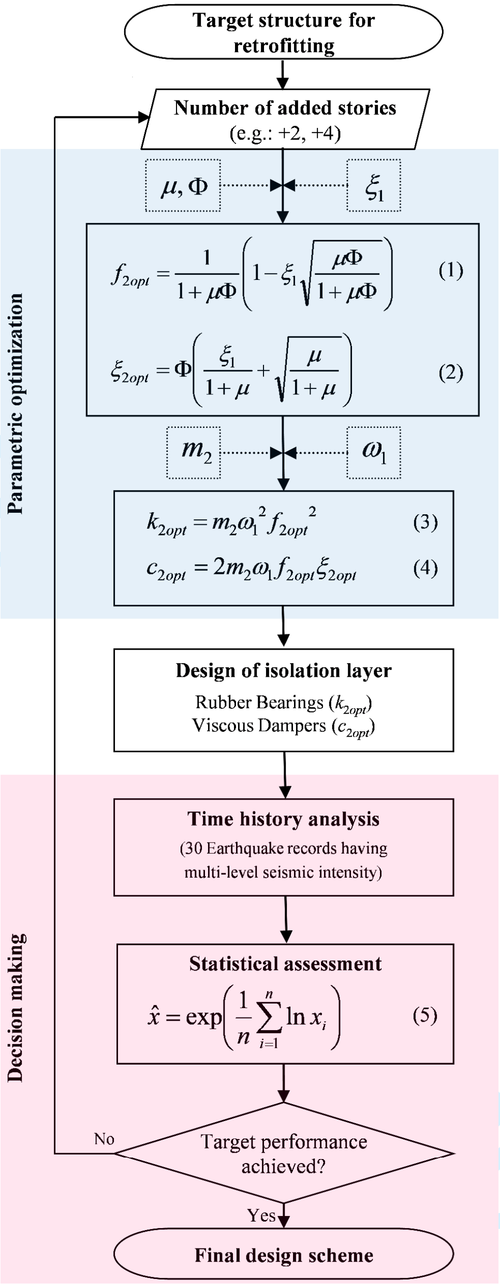
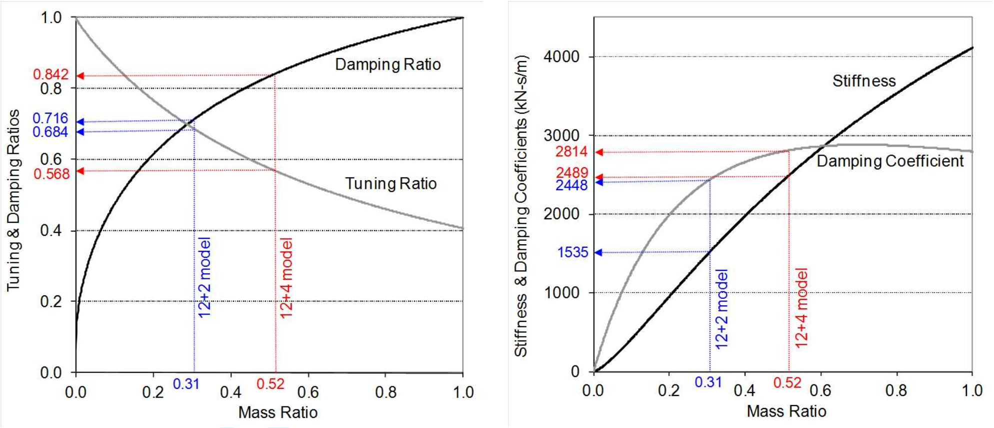


Fig. 3 Design process of the ASI system suggested

Fig. 4(a) shows the optimal tuning and damping ratios versus mass ratio values ranging from 0 to 1, with 5% of internal damping for ‘12+2’ and ‘12+4’ story models. The optimal values for the ‘12+2’ and ‘12+4’ models have been distinguished by blue and red lines at the mass ratios of 0.31 and 0.52 respectively. As the optimal turning frequency values, 0.684 and 0.568 were derived for the models of ‘12+2’ story and ‘12+4’ story, whereas 0.716 and 0.842 damping ratios were used for the two models respectively, despite the potentially over-large damping values provided by these optimal cases. Fig. 4(b) shows the optimal stiffness and damping coefficients for the models of ‘12+2’ (1,535 and 2,448) and ‘12+4’ (2,489 and 2,814) cases respectively.



(a) Tuning and damping ratios (b) Stiffness and damping coefficients

Fig. 4 Optimal parameters for the isolation system

4 The earthquake records used and statistical methodology

The use of suites of accurate seismic time histories is a key feature of this study, with little prior study focusing on the importance of examining a wide range of excitation characteristics. Statistical methods are used to evaluate structural response over the suites, presenting results in a form suitable for performance-based design methods. As the characteristics of seismic excitation are entirely random and unlike other types of vibrational excitation, the use of multiple time history records over a range of seismic levels is also essential for effective controller evaluation, particularly where results from ASI system have been found to be sensitive to the ground motion used.

Sommerville et al. [34] 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 earthquakes contained within the three suites (odd half) are shown in Table 3. It should be noted that although in some cases multiple pairs of earthquake pairs have the same name, these are in fact different time histories, from different recordings of the same earthquake.

Statistical assessment of structural response is an important step in performance-based seismic design. As the characteristics of seismic excitation are entirely random and vary significantly, unlike other types of vibrational excitation, the use of a number of multiple time history records over a range of seismic levels is essential for effective controller evaluation. This approach has been used extensively to develop design guidelines and complete performance assessment of control. The performance measures of interest in this study are therefore evaluated statistically from the individual structural responses from the seismic records within each earthquake suite. Therefore, the choice of statistical tools must ensure the simulation results are accurately represented. To combine the response results across the earthquakes in a suite, log-normal statistics are used [35], since it is widely accepted that the statistical variation of many material properties and seismic response variables is well represented by this distribution provided one is not primarily concerned with the extreme tails of the distribution [36]. 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 log-normal based statistical tools are employed. To combine the response values of a ground motion suite, a log-normal based median of the response quantities of a suite with n earthquakes is defined as in Eq. (5) in Fig. 3. To present a summary of the distribution change between the retrofitted (12+2 and 12+4) and 12-story target data sets, while providing accurate statistical measures that are not highly affected by changes in any single variable, the 50th percentile ($\hat{x}$) response results are presented.

Table 3 Earthquakes scaled within suites (Low, medium and high)

Probability of Exceedance (Suite)	Record	Earthquake Magnitude	Distance (km)	Scale Factor	Duration (sec)	PGA (cm/sec^2)
50% in 50 years (Low)	Coyote Lake, 1979	5.7	8.8	2.28	26.86	578.34
	Imperial Valley, 1979	6.5	1.2	0.4	39.08	140.67
	Kern, 1952	7.7	107	2.92	78.60	141.49
	Landers, 1992	7.3	64	2.63	79.98	331.22
	Morgan Hill, 1984	6.2	15	2.35	59.98	312.41
	Parkfield, 1966, Cholame 5W	6.1	3.7	1.81	43.92	765.65
	Parkfield, 1966, Cholame 8W	6.1	8	2.92	26.14	680.01
	North Palm Springs, 1986	6	9.6	2.75	59.98	507.58
	San Fernando, 1971	6.5	1	1.3	79.46	248.14
	Whittier, 1987	6	17	3.62	39.98	753.70
10% in 50 years (Medium)	Imperial Valley, 1940, El Centro	6.9	10	2.01	39.38	452.03
	Imperial Valley, 1979, Array #05	6.5	4.1	1.01	39.38	386.04
	Imperial Valley, 1979, Array #06	6.5	1.2	0.84	39.08	295.69
	Landers, 1992, Barstow	7.3	36	3.2	79.98	412.98
	Landers, 1992, Yermo	7.3	25	2.17	79.98	509.70
	Loma Prieta, 1989, Gilroy	7	12	1.79	39.98	652.49
	Northridge, 1994, Newhall	6.7	6.7	1.03	59.98	664.93
	Northridge, 1994, Rinaldi RS	6.7	7.5	0.79	14.95	523.30
	Northridge, 1994, Sylmar	6.7	6.4	0.99	59.98	558.43
	North Palm Springs, 1986	6	6.7	2.97	59.98	999.43
2% in 50 years (High)	Kobe, 1995	6.9	3.4	1.15	59.98	1258.00
	Loma Prieta, 1989	7	3.5	0.82	24.99	409.95
	Northridge, 1994	6.7	7.5	1.29	14.95	851.62
	Northridge, 1994	6.7	6.4	1.61	59.98	908.70
	Tabas, 1974	7.4	1.2	1.08	49.98	793.45
	Elysian Park (simulated)	7.1	17.5	1.43	29.99	1271.20
	Elysian Park (simulated)	7.1	10.7	0.97	29.99	767.26
	Elysian Park (simulated)	7.1	11.2	1.1	29.99	973.16
	Palos Verdes (simulated)	7.1	1.5	0.9	59.98	697.84
	Palos Verdes (simulated)	7.1	1.5	0.88	59.98	490.58

5 Performance Results

The analytical results for the buildings described are obtained to check the performance of each structural control case. To investigate the efficiency of the applied control systems, the 50th (median) percentile responses of the '12' story, '12+2' story, and '12+4' story models under the suites (low, medium and high) are compared over all floors and the response envelopes are presented in Figs 5-8. The peak relative displacements, interstory drift ratios, story shear forces and total accelerations for all floors are calculated as control effectiveness indices. In addition, to compare the ASI systems developed, the summarized reduction factors to the uncontrolled target model over 1st to 12th floor have been depicted in Fig. 9. This is a possible summarizing approach, since the most of the response envelops are reasonably uniform or linear, and the distribution of the demands are fairly equivalent and the slight differences are apparent with uncontrolled cases developed.

Overall, it is observed that the ASI control provides satisfactory reductions and that control performance is clearly dependent on the specific earthquakes and suites. In addition, the control effects of the ASI systems are not so influenced by the amount of added mass (12+2 vs. 12+4) and are relatively more pronounced under the low and high suites than medium suite. On average, the '12+2' or '12+4' story ASI system received considerably more input energy than the original 12-story building. However, the share of structural components of the system from this energy remained small. Reductions in responses are fairly modest considering that the retrofitted structures have fourteen and sixteen stories instead of the twelve of the original configuration. In addition, care must be taken not to assume that ASI strategies which reduce statistical values for the ground motion sets will reduce demands for all individual excitations.

The maximum displacements of each level increase steadily over the height of the level under the all suites as shown in Fig. 5. Both ASI systems (12+2 and 12+4) produce very similar displacements under the medium suite (Fig. 5(b)). However, under the high suite, the '12+4' ASI systems show relatively more reductions, and the different distribution of displacement demands over the levels is fairly apparent. Under the low suite, the '12+4' ASI system demonstrates more reduced demands from 9th to 16th floors. The 50th percentile reduction factors of the maximum displacements by the '12+2' ASI system are 0.669~0.811 under the suites, while 0.637~0.778 by the '12+4' ASI system as shown in Fig. 9.

The envelopes of the retrofitted interstory drifts are relatively uniform and the drifts are decreased over the 11th floor to the 16th floor, especially above the isolation layers. In particular, the drift envelops of both isolation systems (12+2 and 12+4) cross one another at the 11th, 6th and 10th floor under the low, medium and high suites respectively. Overall, the ‘12+4’ ASI systems present more reliable and constant drift demands along the height of the original 12-story structures except for some upper floors under the medium suite. The 50th percentile reduction factors of the interstory drifts are 0.723~0.825 by the ‘12+2’ ASI systems, while 0.702~0.827 by the ‘12+4’ ASI systems under the suites. Again, the retrofitted ASI systems prove to be more effective under the low and high suites than the low suite.

The story shear forces produced by the ASI systems also show good reductions based on the results from the maximum displacements. Under the all suites, the shear force demands are reduced and, these response reductions are increased for 12+4 cases and under the high suite. In spite of adding 24% mass (12+2) and 40% mass (12+4) to the buildings, the method of construction that uses added stories at the interface actually reduces the seismic demand in the stories under the all suites of the earthquake records considered. The ‘12+4’ ASI system under the medium suite results in greater shear force reduction factor of 0.676.

As seen in Fig. 8, the acceleration distributions over the height are fairly similar and the ASI systems show very uniform demand profiles under the all suites. The added large-damped viscous dampers of the systems have the benefit of being capable of reducing the acceleration demands on the structures. In particular, the acceleration responses of the isolated stories have a significant reduction in all cases. The reason for these reductions is again that the added upper stories are isolated from the main structure, so base excitation is not directly transmitted to the separated upper stories of the structure. In another word, this reflects the effective interruption of energy flows between both upper and lower stories of the structures. The 50th percentile reduction factors of accelerations by the ‘12+2’ ASI systems are 0.684~0.760, while 0.638~0.730 by the ‘12+4’ ASI systems under the suites as shown in Fig. 9.

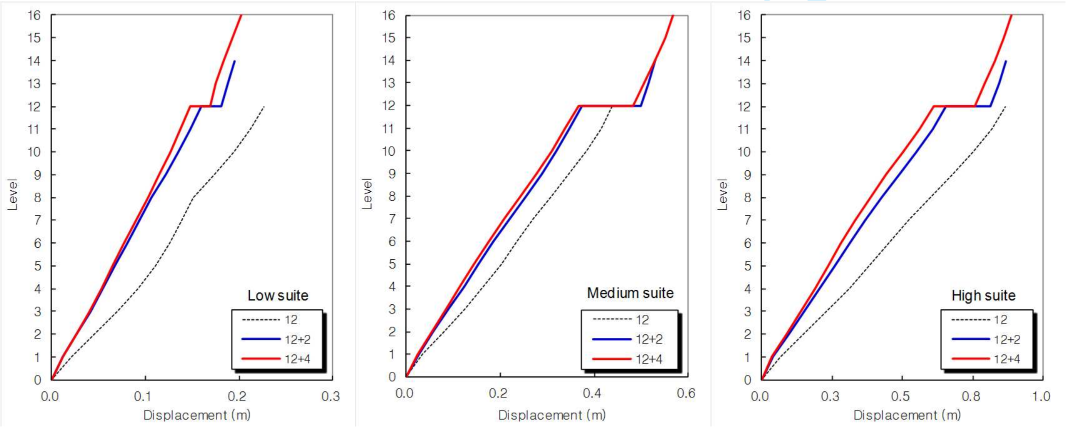


Fig. 5. Displacement profiles of the target and retrofitted models (Low (a), medium (b) and high (c) suites)

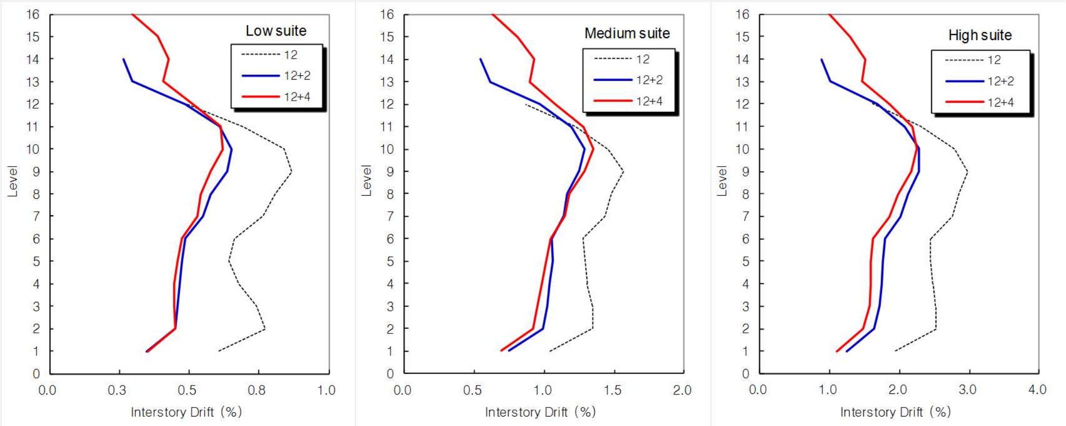


Fig. 6. Interstory drift profiles of the target and retrofitted models (Low (a), medium (b) and high (c) suites)

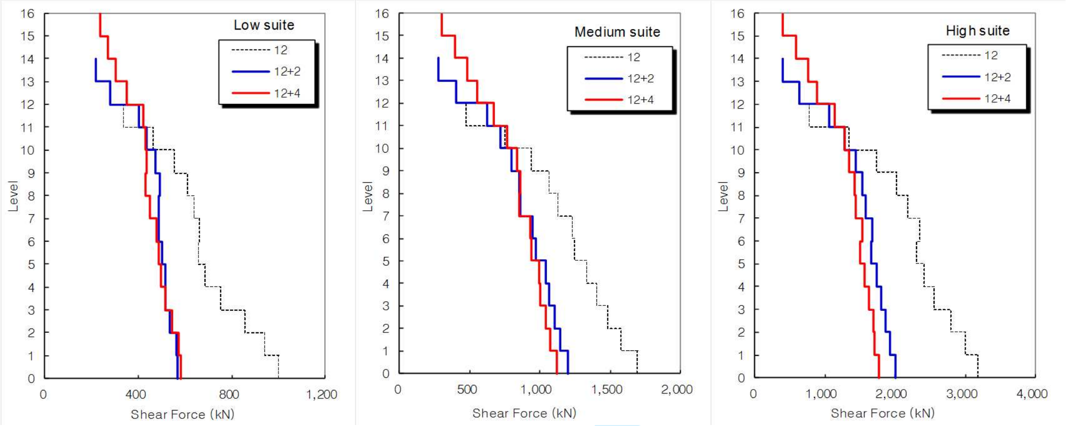


Fig. 7. Story shear force profiles of the target and retrofitted models (Low (a), medium (b) and high (c) suites)

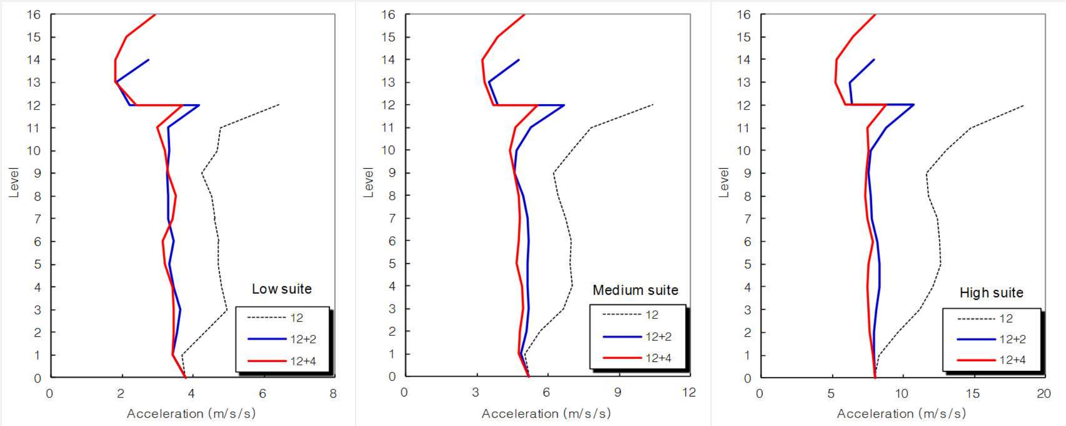


Fig. 8. Acceleration profiles of the target and retrofitted models (Low (a), medium (b) and high (c) suites)

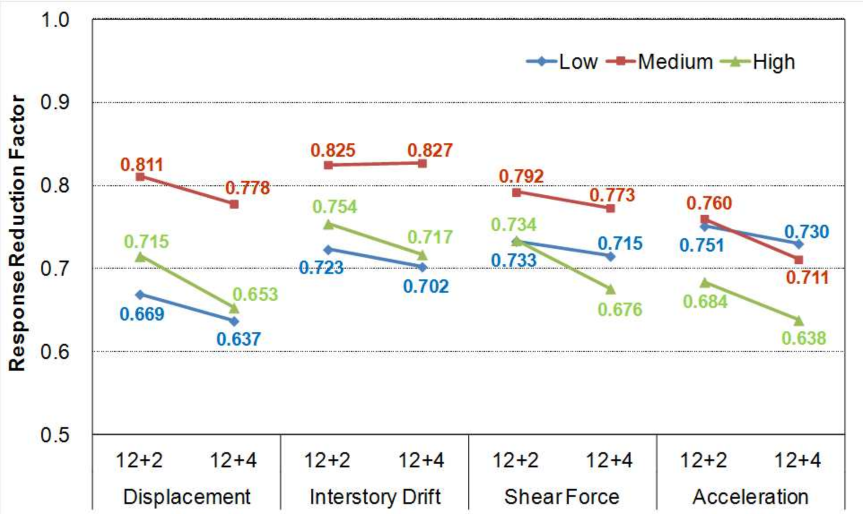


Fig. 9. Summarized response reduction factors of the ASI systems (Low, medium and high suites)

6 Conclusions

This study explored the response characteristics for added stories isolation (ASI) systems when new stories are added as the tuned mass on existing structures. Overall, the results are quite promising and reliable. Intuitively, adding more stories to the existing building is primarily an attempt to control the fundamental mode of vibration of the original structure by a damping mechanism located on the top of the building. Therefore, from a structural point of view, the additional stories are solely meant to be a support for the reaction of the damping mechanism. In the new system, the mass of added stories contributes mostly to the fundamental mode of vibration, which is properly isolated by a long natural period. The second mode of the retrofitted structures, which has the mass of the original building, is now accompanied by a large damping ratio as was intended, by design thus describing how energy and force transmitted to the system are reduced.

Overall, the details and results of a set of comparative studies were performed to assess the feasibility and effectiveness of such isolation systems. The analysis has demonstrates the validity of realistic ASI systems for consideration in future design and construction in an analytical setting. Furthermore, this new system has the meaning of increase the impact of passive isolation methods by broadening their application domain to include tall structures for which base isolation methods have not heretofore been considered feasible, such as high-density residential apartment and commercial structures. These tall residential structures are becoming increasingly common in large urban centers, and the need for ensuring structural integrity and performance in the face of large environmental loads are critical. The extension of passive base isolation applications to these structures will significantly advance the state of structural energy management and broaden its applicability by adding the adaptability of active or semi-active feedback control systems. This feature is significant as the primary drawback of passive, tuned systems is the loss of performance over the (long) lifecycle of the structure as its fundamental dynamic change over time.

In view of these findings above, the proposed ASI 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. It can be concluded that the suggested ASI system is directly relevant to future structural design and construction in the area of structural energy management, given the level of seismic risk around many of our major cities in the world.

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