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ORIGINAL ARTICLE

Seismic Performance Evaluation of Various Passive Damping Systems in High and Medium-Rise Buildings with Hybrid Structural System

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Abstract:

The main aim of this manuscript is to bridge existing knowledge gaps by undertaking comprehensive investigation of several high and medium-rise structures in Iran with different damping devices embedded within cut outs of shear walls. To further extend understanding of damping devices embedded within cut outs of shear walls, these structures are treated under a variety of different earthquake excitations and the results are compared in order to capture their advantages in creating efficient damping systems. The research will address the needs of local industries. It aims to carry out a comprehensive investigation on seismic mitigation of high and medium-rise structures with different damping devices embedded within cut outs of shear walls at different locations across the height of each structure. Nonlinear finite element modeling approach has been used in the current study.

Keywords:*Passive Damping, Seismic, Hybrid Structural System, FEM*

1. INTRODUCTION

Earthquakes are one of nature's greatest hazards to life on this planet and have destroyed countless cities and villages on virtually every continent. They are one of man's most feared natural phenomena due to major earthquakes producing almost instantaneous destruction of buildings and other structures. Additionally, the damage caused by earthquakes is almost entirely associated with manmade structures. As in the cases of landslides, earthquakes also cause death by the damage they induce in structures such as buildings, dams, bridges and other works of man. Unfortunately many of earthquakes give very little or no warning before occurring and this is one of the reasons why earthquake engineering is complex[1-2].

Some of the major problems relating to earthquake design are created by the original design concept chosen by the architect. No engineer can truly transform a badly conceived building into an earthquake resistant building. The damages which have occurred during earthquake

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events clearly demonstrate that the shape of a building is crucial to how they respond. The ideal aspects of a building form are simplicity, regularity and symmetry in both elevation and plan. These properties all contribute to a more predictable and even distribution of forces in a structure while any irregularities are likely to lead to an increased dynamic response, at least in certain locations of the structure. [3-5]

Also buildings, which are tall in comparison to their plan area, will generate high overturning moments while buildings with large plan areas may not act as expected due to differences in-groundbehaviour, which are not always predictable. This causes different parts of the building to be shaken differently creating obvious problems. Torsion from ground motion could be of great concern due to eccentricity in the building layout. For instance if the center of mass (gravity) is not in the same position as the center of resistance a torsional moment about a vertical axis will be created which will have to be designed for. In order to achieve satisfactory earthquake response of a structure, three methods can be identified as being practical and efficient. These are; base isolation, energy absorption at plastic hinges and use of mechanical devices to provide structural control.[6-19]

2. SCOPE OF THE STUDY

The use of passive energy dissipation devices has become very popular in the recent years. However, the vast majority of applications was realized within frame structures, while investigations on use of damping devices within cut outs of shear wall is still very limited. For this reason the aim of this research is to investigate the behaviour of multi-storey frame-shear wall building structures under earthquake loads with damping devices strategically located within the cut outs of the shear wall. The research will evaluate the influence of different damping systems on the overall seismic response of the structure.[20]

3. SEISMIC ISOLATING SYSTEMS

In order to control the vibration response of high and medium rise buildings during seismic events, energy absorbing passive damping devices are most commonly used for energy absorption. Today there are a number of types of manufactured dampers available in the market, which use a variety of materials and designs to obtain various levels of stiffness and damping. Some of these include friction, yielding, viscoelastic and viscous dampers. These dampers are usually installed between two load bearing elements (walls or columns) in new buildings. In existing buildings, which require retrofitting, they could be installed in cut-outs of shear walls, as evidenced from recent investigations. An effective damping system can result in higher levels of safety and comfort, and can also lead to considerable savings in the total cost of a building[8-11,21-27, 38]. Some of the most common damping devices and the ones which are investigated in this study are listed and briefly described here.

- *Yielding steel bracing systems*
- *Lead Extrusion Damper (LED)*
- *X-braced damper*
- *Uniaxial friction damper*
- *Sumitomo friction damper*
- *Solid VE dampers*
- *Metallic dampers*
- *Slotted bolted damper*
- *Viscous-damping wall system*
- *Tuned Mass Damper (TMD)*
- *Tuned Liquid Damper (TLD) and Tuned Liquid Column Damper (TLCD)*
- *ADAS and TADAS damping systems*

3.1. Uniaxial friction damper

Uniaxial friction damper (Fig. 1) manufactured by Sumitomo Metal Industries Ltd., utilizes a slightly more sophisticated design. The pre-compressed internal spring exerts a force that is converted through the action of inner and outer wedges into a normal force on the friction pads. These copper alloy friction pads contain graphite plug inserts, which provides dry lubrication. This helps to maintain a consistent coefficient of friction between the pads and the inner surface of the stainless steel casing.[39]

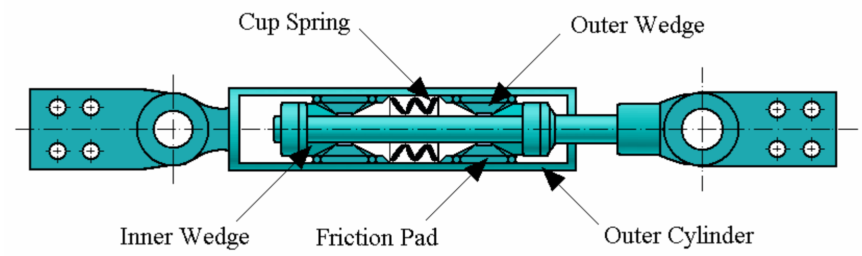

Figure 1: Uniaxial friction damper

3.2. Sumitomo friction damper

Sumitomo friction damper was investigated by [8]. The inventors performed experimental and numerical examinations of this damper installed on 1/4-scale 9 storey steel frame in conjunction with chevron brace assembly. The performance of the friction dampers was outstanding. The hysteresis loops showed very consistent, nearly ideal Coulomb behaviour throughout the duration of the test and approximately 60% of the input energy was dissipated in the dampers.

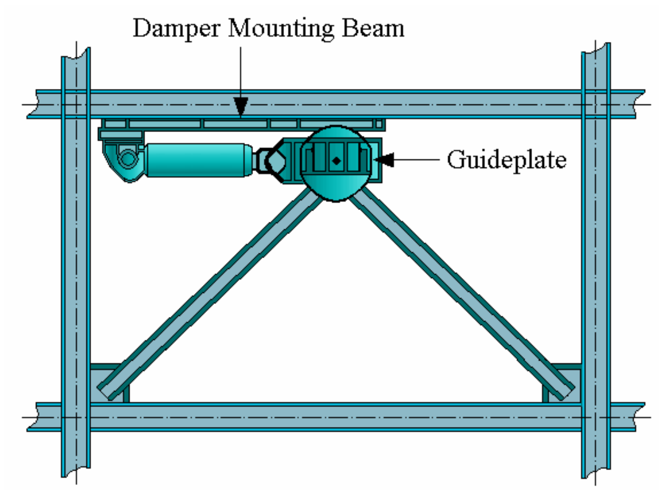

Figure 2.Installation of uniaxial friction damper in steel frame

3.3. Solid VE dampers

Solid VE dampers are constructed from constrained layers of acrylic polymers or copolymers and designed to produce damping forces through shear deformations in the VE material. When deformed, the VE materials exhibit the combined features of an elastic solid and viscous liquid i.e. they return to their original shape after each cycle of deformation and dissipate a certain amount of energy as heat.[40].

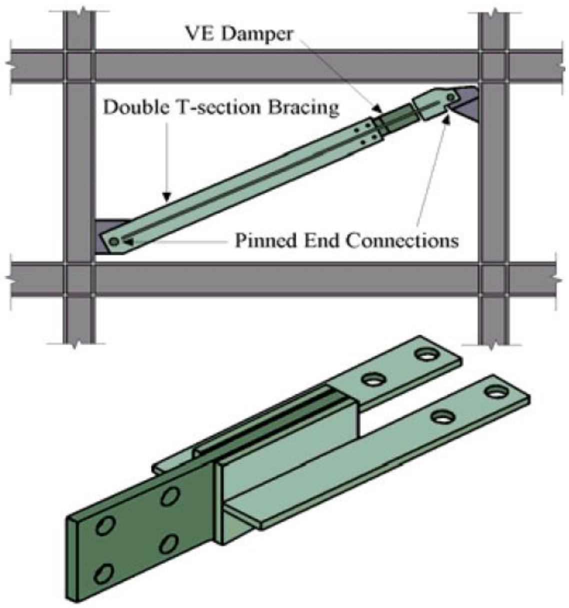

Figure 3. Typical VE solid damper

4. DYNAMIC ANALYSIS

The time history analysis determines the response of a structure due to forces, displacements, velocities or accelerations that vary with time. There are two types of this method, first is direct integration and the second, modal superposition [28-29].Modal superposition is only suitable for linear analysis, whereas direct integration can be used also for nonlinear analysis. The direct integration utilizes a step-by-step solution of equation of motion, which is generally described as:

$$\mathbf{M\ddot{U} + C\dot{U} + KU = F(t)} \quad (1)$$

Where, *M,C,K* are the mass, the damping, and the stiffness matrices, respectively, U , $\dot{U}$, and $\ddot{U}$ are the displacement, velocity and acceleration vectors, respectively, *F(t)* is the vector of applied forces, which may varied with time. The most popular integration scheme is the Newmark-β method, which is implicit and unconditionally stable. The following approximations are made in this method:

$$\{\dot{U}\}_{t+dt} = \{\dot{U}\}_t + (\{\ddot{U}\}_t + \{\ddot{U}\}_{t+dt})\frac{dt}{2} \quad (2)$$

$$\{U\}_{t+dt} = \{U\}_t + \{\dot{U}\}dt + \left(\left(\frac{1}{2} - \beta\right)\{\ddot{U}\}_t + \beta\{\ddot{U}\}_{t+dt}\right)(dt)^2 \quad (3)$$

Where, *dt*is the time step of the analysis, and β is the structural damping depend on an amplitude decay factor, but usually a value of 0.25 is used.

5. METHODOLOGY OF THE RESEARCH

This study comprehensively investigates the seismic response of 30 and 16 storeyframe-shear wall structures with dampers located within cut-outs. Two types of damping mechanisms were investigated. The first damping mechanism involves the use of friction damper; the second damping mechanism involves the use of VE damper.

5.1. Finite Element Analysis:

Finite Element (FE) methods have been employed in this research to model, analyze and investigate the effects of the two types of damping devices on the seismic response of structures. For the purpose of this study, the programs selected for the numerical analysis have been SAP2000 and LUSAS Standard Version.

A direct integration dynamic analysis was selected to obtain the response of the structure under seismic loading. This analysis assembles the mass, stiffness and damping matrices and solves the equations of dynamic equilibrium at each point in time. The response of the structure is obtained for selected time steps of the input earthquake accelerograms. To study the effectiveness of the damping system in mitigating the seismic response of the buildings in this study, the maximum displacements and accelerations at the top of the structures are obtained from the results of the analysis and compared with those of the undamped building structure.[30]

5.2. Boundary conditions:

The earthquake events used in this study were recorded as time-history accelerations in the horizontal plane. The acceleration was applied in the X-direction at the base of the structure, as shown in Fig. 4.The support at the base of the structure was restrained against translation in the Y-direction, and rotation about the Z-axis, thereby allowing only the X-direction translation.

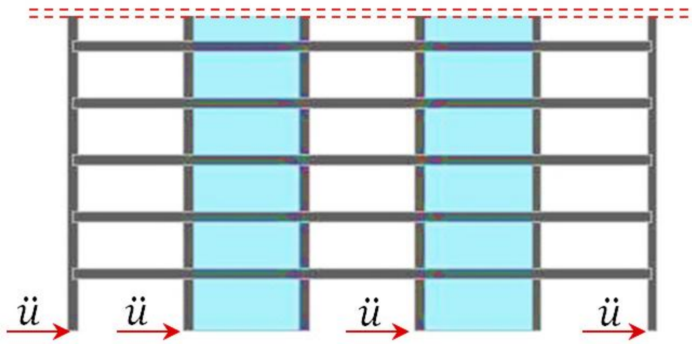

Figure4. Model location of applied acceleration

5.3. Material properties:

Concrete material properties were chosen for the models since many multi-storey buildings in IRAN are constructed by using reinforced concrete. The concrete had a compressive strength, f'_c of 35 MPa, Young's modulus, E_c of 30,000 MPa, which reflects an assessment assuming predominantly elastic response with little cracking, Poisson's ratio, υ of 0.2, and density, ρ of 2500 kg/m^3. No internal damping was considered for the concrete since it was assumed small in relation to the damping provided by the damping devices. Structural steel was used to model friction dampers with yield strength, f_y of 400 MPa, and Young's modulus, E_c of 207,000 MPa, Poisson's ratio υ of 0.3 and density, ρ of 7800 kg/m^3.

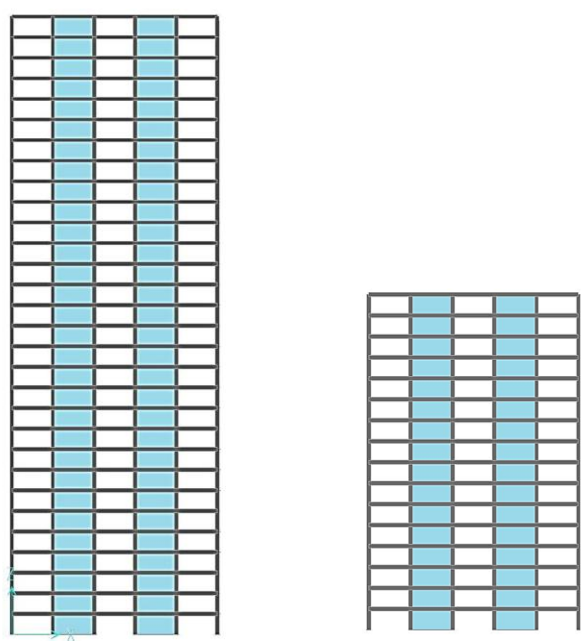

Figure 5.Modelled structures of 16 and 30 storey buildings in FE softwares

5.3.1. Nonlinear concrete material modeling:

One of the methods to model nonlinear concrete material modeling is multi-cracking concrete with crushing model. This model stimulates the nonlinear behaviour of concrete in both compression and tension at the same time. Therefore, the yield function consists of the two main parameters which are the tension softening of concrete and compression crushing. As a result, this model is suitable cracking and crushing failure at the same time[31]. The typical behaviour of the tension softening effect and concrete crushing is shown as below:

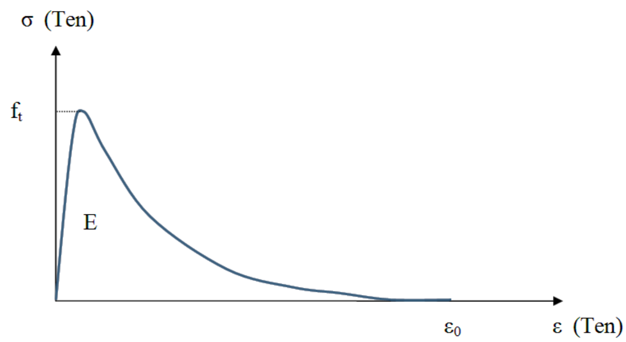

Figure 6. Tension Softening Behaviour of Concrete

Fig. 6 shows that the tension behaviour of the concrete. The peak stress of the graph is the tensile strength, f_t and the slope is the elastic modulus value, E. The peak stress is end up at the end of tension stiffening value, $ε_o$. This behaviour is important when model the concrete crack. The concrete crack happens to be loss its strength gradually once the concrete tensile strength reaches the peak. Therefore, the problem arises when the crack is modeled as discrete crack because it would increase the ductility of the concrete which may not be true.

Table 1. Material Properties for Concrete Components

Elastic	
Young Modulus	*30000MPa*
Poisson Ratio	*0.2*
Plastic (Cracking & Crushing Model)	
Tensile Strength	*4 N/mm^2*
Compressive Strength	*40 N/mm^2*
Strain at Peak Compressive Stress	*0.0030*
Strain at End of Compressive Softening Curve	*0.0035*
Strain at End of Tensile Softening Curve	*0.13-0.8*

5.3.2. Nonlinear steel material modeling:

To choose a suitable model, we have to know the behaviour of the steel. The model must able to stimulate the behaviour of the steel. Here we choose stress potential method. The stress potential method able to simulate the yield behaviour in all direction of stress space required under multiaxial stress. Besides that, it could also show the hardening properties of steel in terms of hardening gradient and effective plastic strain [31]. The graph is shown in Fig. 7.

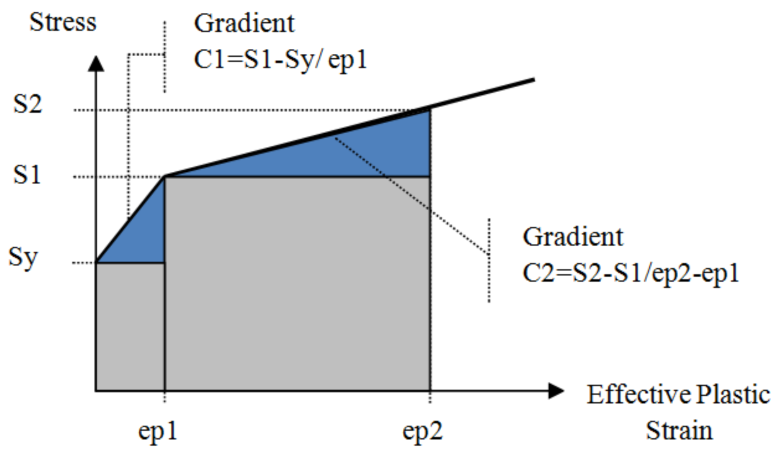

Figure 7: Hardening Properties of Steel

Table 2: Material Properties for Reinforcement

Elastic	
Young Modulus	*207000 MPa*
Poisson Ratio	*0.3*
Plastic (Stress Potential Model)	
Initial Uniaxial Yield Stress	*560 N/mm²*
Hardening Gradient	*2121*
Plastic Strain	*5*

5.4. Damper models:

5.4.1. Friction damper model:

The first damping mechanisms employed in this study have been represented by friction dampers. The initial focus of this research was on the development of a model, which represents the real behaviour of friction dampers. This task was achieved by modeling the frictional contact between two tubes, which slide one inside the other.

5.4.2. Viscoelastic damper model:

The second damping mechanisms employed in this study are represented by VE dampers. Dampers are modelled as a linear spring and dash-pot in parallel (known as the Kelvin model) where the spring represents stiffness and the dashpot represents damping. In a study which was done on 1993 [6] stiffness and damping coefficients defined as follows:

$$k_d = \frac{G'A}{t} \quad (4)$$

$$C_d = G''A/\omega t \quad (5)$$

where, A, is the shear area of the VE material, t, is the thickness of the VE material, ω, is the loading frequency of the VE damper, G', is the shear storage modulus, and G" is the shear loss modulus. The following equations were used to obtain the moduli of the VE material as defined by[6]:

$$G' = 16.0\omega^{0.51}\gamma^{-0.23}e^{\left(\frac{72.46}{Temp}\right)} \quad (6)$$

$$G'' = 18.5\omega^{0.51}\gamma^{(-0.20)}e^{((73.89/Temp))} \quad (7)$$

Where, γ is the shear strain and Temp is VE material temperature. This model approximates the behaviour of a VE damper under vibratory loading to within 10%, which was considered sufficiently accurate for the purposes of this study. As it can be seen from equations 6 and 7, the temperature of VE material significantly influences its mechanical characteristics. However, experimental results conducted by [32] have shown that variation in the damper temperature due to dynamic excitation become negligible after several loading cycles as an equilibrium temperature is reached between the surroundings and the damper. In the present study the temperature was kept constant at 23°C during the entire investigation.[32]

5.5. Description of 16 and 30 storeys frame-shear wall structures:

The structural models, treated in this research have been predominantly represented by two types of frame-shear wall structures. The first set of models designated by S represents two-dimensional 16-storey frame-shear wall structures and the second setof models designated by X represents two-dimensional 30-storey frame-shear wall structures. After the preliminary convergence study, the concrete shear walls in LUSAS were constructed from 2016 S4R5 shell elements using shell elements of designation S4R5, having 4 nodes per element and 5 degrees of freedom at each node. The dimensions of the shear walls were 6m wide and 0.4 m thick. The columns and beams were located on either side of the wall had cross-sectional dimensions of 0.7 × 0.7 m and 0.65 × 0.4 m respectively, and the beam spans were 6.0 m.

The height between storeys was set at 3.5 m, which made the overall height of the structures to be 56.0 m and 105.0 m. A lumped mass of 15,000 kg at each beam-column and beam-shear wall junction was used to account for mass transferred from slabs and beams.

5.6. Damper placement in 16 and 30 storeys frame-shear wall structures:

One of the main aims of this study was to investigate the efficiency of energy dissipating dampers in vibration control for variety of placements under different earthquake loads [33]. For this purpose ten different damper placements were used to study the influence of location on the seismic response of these models. These models were designated by S1, S3, S6, S9, S12 and S15 for single damper placements and by S1-4, S5-8, S9-12 and S13-16 for four dampers placement within the models. As can be seen in Figs. 8 and 9, the designating numbers correspond to location of the storey at which dampers were placed. The undamped structure (Fig. 5) was also analyzed in order to compare results.
Damper placements for 30 storeys structure designated by X1, X6, X12, X18, X24 and X30 for single damper placements and by X1-5, X6-10, X11-15, X16-20, X21-25 and X25-30 for five dampers placements within the models.

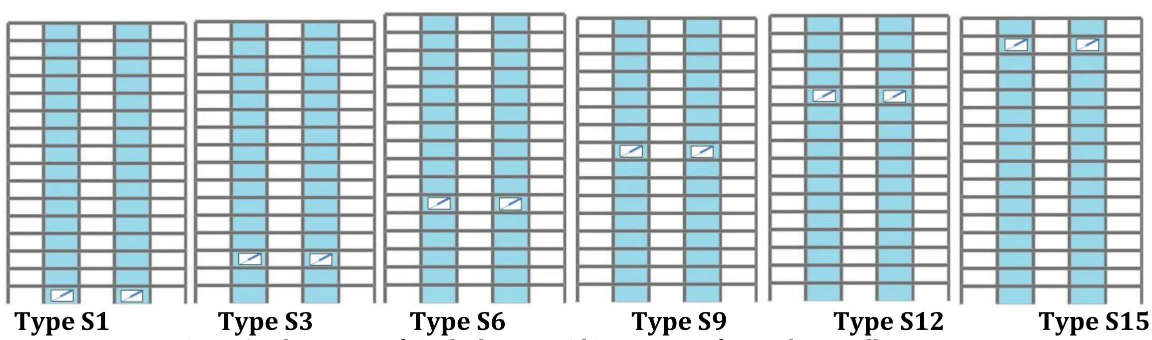

Figure 8: Placements of single damper within 16-storey frame-shear wall structures

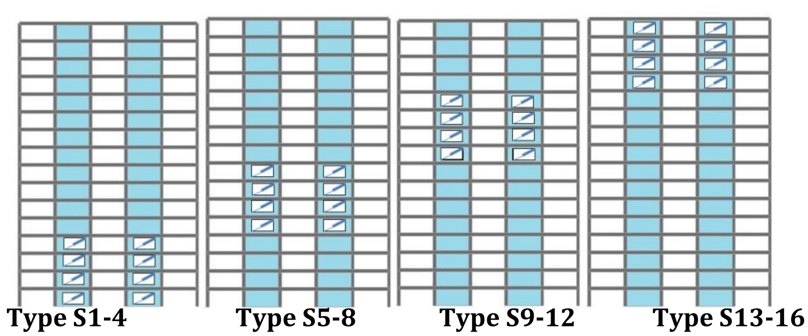

Figure9: Placements of three dampers within 16-storey frame shear wall structures

5.7. Structural model with friction damper – diagonal configuration:

Details of the diagonal friction damper located within shear wall of the frame-shear wall model can be seen in Fig. 10 where a 3.5 m wide by 3.5 m high wall section was cut out and replaced by the damper. This damper was modelled as a pair of diagonal tubes each with a thickness of 50 mm, and with one tube placed within the other.

- The outer tube having an inner diameter of 180 mm and length 3.75 m was modelled using 264 S4R5 shell elements.
- The inner tube having an outer diameter of 178 mm and length 3.75 m was modelled using 252 S4R5 shell elements.

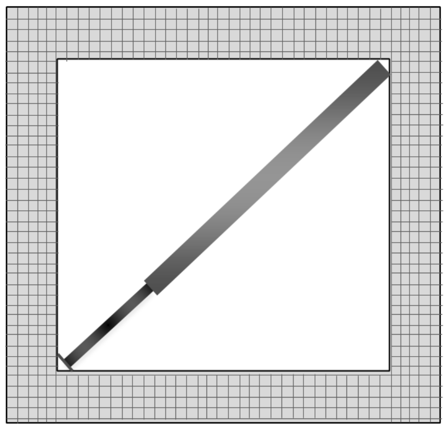

Figure 10. Structural details of diagonal friction damper

The response of this model as well as all others were investigated under the El Centro, Bam, Kobe and Tabas earthquake excitations which will be described later. It's worth mentioning that the connection between FR damper and the shear walls is modelled by a pinned joint element with elasto-plastic behavior and special interface elements with friction-sliding properties have been used for modeling the friction behavior between the tubes.

5.8. Structural models with VE damper – diagonal configuration

The concrete frame-shear wall was modelled using the same FE mesh, material properties and dimensions as in the previous models. Detail of the diagonal VE damper located within the cut out of the shear wall can be seen in Fig. 11. The properties of the damper for 16-storeys models were at first calculated as $K_d = 10 \times 10^6$ N/m and $C_d = 63 \times 10^6$ Ns/m based on double layer damper in parallel with dimensions of 1,850 mm by 300 mm by 10 mm and the values G'= 900,000 Pa and G"= 300,000 Pa. These moduli were calculated using the loading frequency f = 0.718 Hz, which corresponded to the fundamental frequency of this structure model.

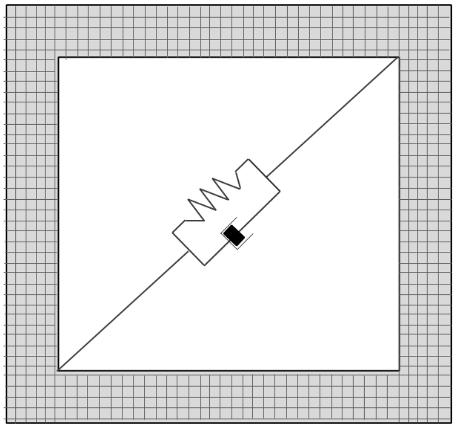

Figure 11. Structural details of diagonal VE damper

5.9. Input earthquake records:

The earthquake records, which were selected to investigate the dynamic response of the models, are:

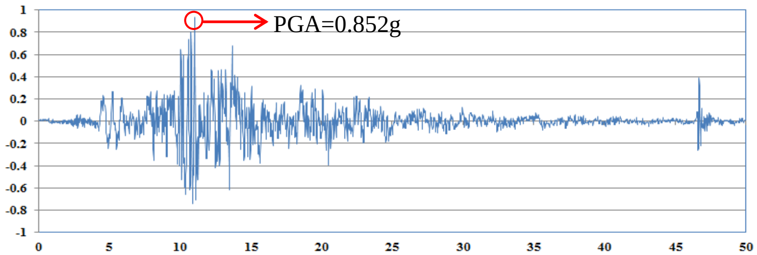

Figure 12: TABAS earthquake

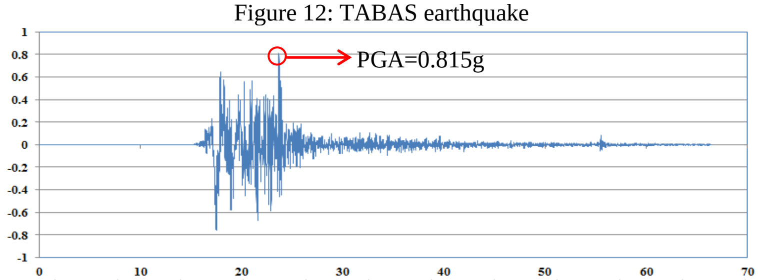

Figure 13:BAM earthquake

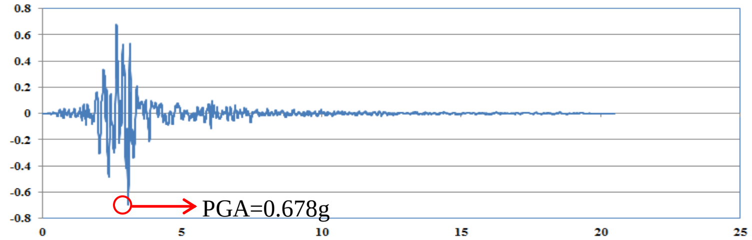

Figure 14: KOBE earthquake

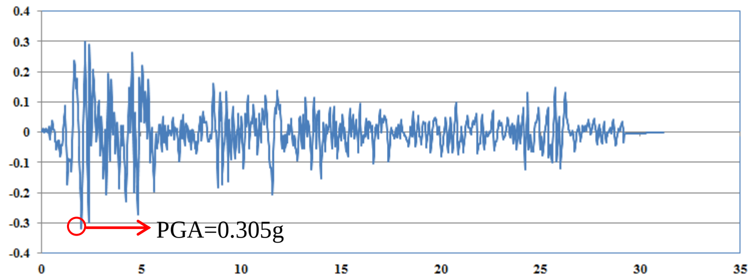

Figure 15. ELCENTRO earthquake

5.10. Verification of the Results:

One of the available alternatives to examine the validity of research results is to use the analytical benchmark models proposed by the American Society of Civil Engineers (ASCE). A committee of ASCE on Structural Control developed a benchmark study, focusing on the comparisons of structural control algorithms for the benchmark structural control problems. Some of these algorithms have been experimentally confirmed at the Laboratory of University of Notre Dame's.The primary objective of this project was to develop benchmark models to provide systematic and standardized means by which a variety of control methods can be examined. Realizing of these objectives allow implementation of innovative control approaches for dynamic hazard mitigation. [34-37]

The researchers from Faculty of Engineering, University of Technology Sydney participated in this benchmark project and have published several experimental works, which were conducted in their University's laboratories. Some of these testings were conducted on the five-storey benchmark model subjected to different earthquake excitations.[38-40] In order to verify the validity of the present research project, similar model was created and treated under the same earthquake excitations in the computer program LUSAS. The results are compared and evaluated with the results of experimental testing.

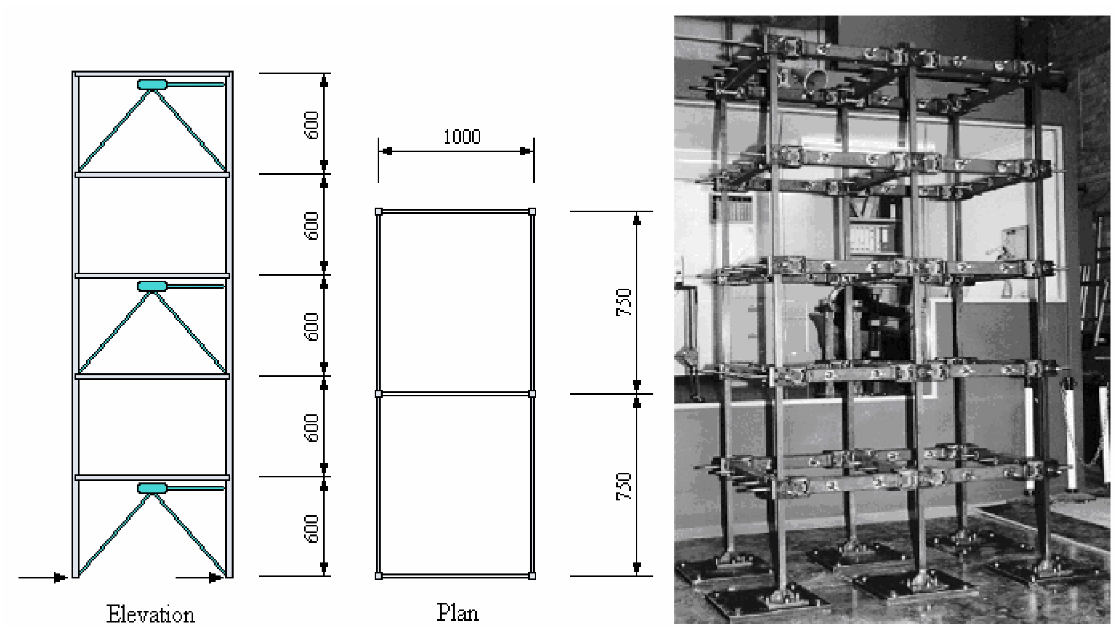

Figure 16. Elevation and plan of the five-storey benchmark model

6. RESULTS AND DISCUSSIONS

The results from the finite element analyses of two types of high and medium-rise structure are presented in this section. First type is represented by a 56 m high shear wall structure embedded with two different damping systems, namely friction and VE diagonal dampers. These damping systems were installed within cut outs of shear wall at ten different damper placements. Seismic analyses were carried out with one type of damper at one placement at a time. Efficiency of these damping systems was investigated under four different earthquake excitations. This was the first structure treated in this research to determine feasibility of the procedure. The second type is a 30 storey building with 105 heights with hybrid structural system (Moment frame + Shear wall + Damper).

The results of percentage reduction in tip deflection of the structure embedded with damper of varying properties display overall very high performance. The results reveal the high level of sensitivity of the structure to varying damping properties of dashpot. The best performance with the highest reduction of 42.3% was recorded for dashpot with damping parameter of $C_d = 70 \times 10^6$ Ns/m. The second highest reductions were recorded for dashpot with damping parameter of $C_d = 60 \times 106$ Ns/m, it was followed by $C_d = 50 \times 106$ Ns/m and $C_d = 80 \times 106$ Ns/m with reductions only slightly lower. In general, it can be stated that dashpot with the values of damping in the range from $C_d = 20 \times 106$ Ns/m to $C_d = 140 \times 106$ Ns/m experienced very high and stable performance, while decrease in the performance was significant when value of the damper was moved out of this range.

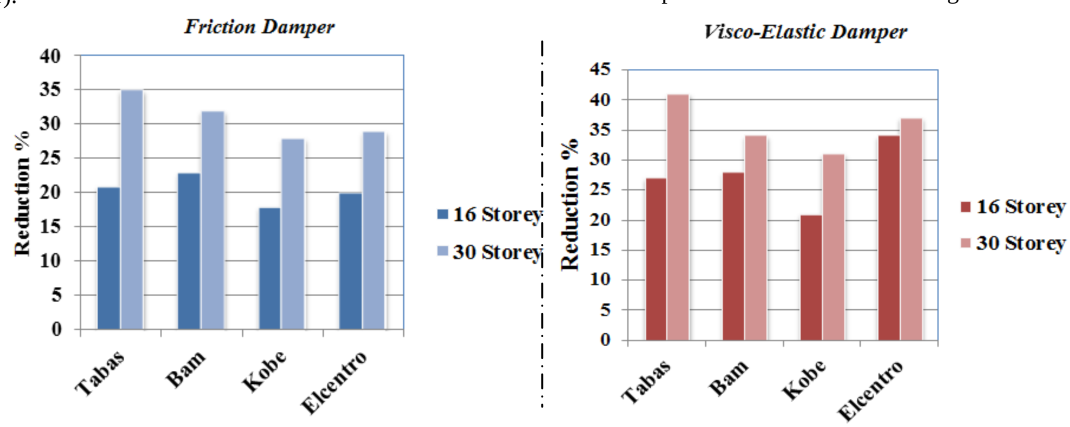

Figure 17. Average tip deflection reductions for different damping systems(Best Placement Results)

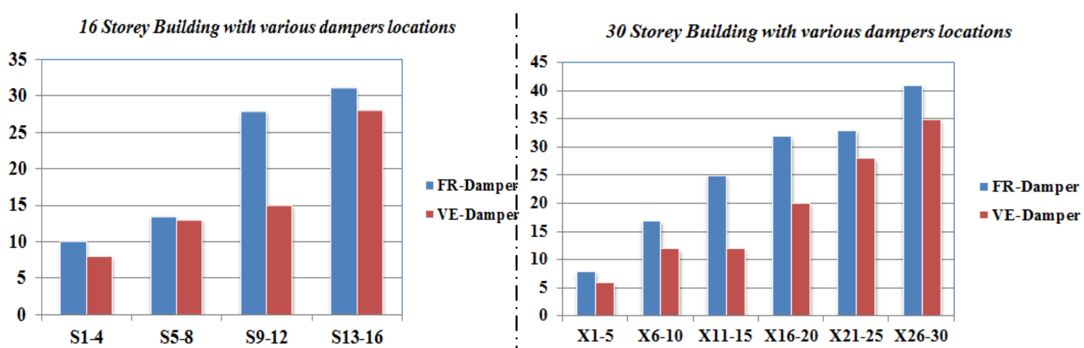

Figure 18.Average tip deflection reductions (under four earthquakes) for different damper locations

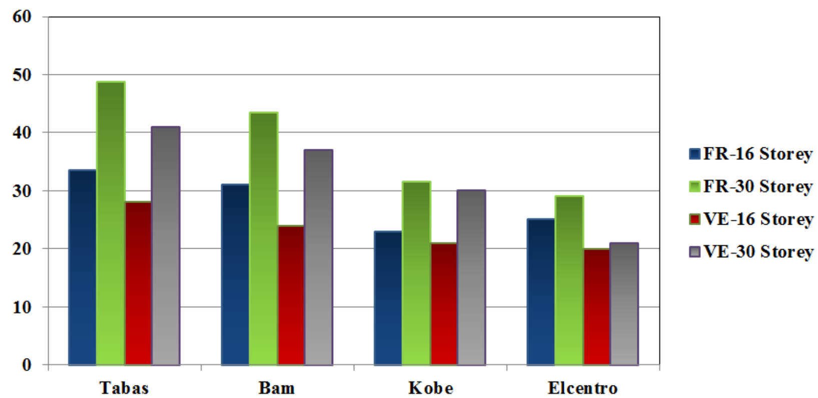

Figure 19.Average tip acceleration reductions for different damping systems under 4 earthquakes(Best Placement Results)

6.4. Response of the structure under four earthquake excitations:

The 30-storey frame-shear wall structural model was further investigated under four earthquake excitations. Based on results reported in the previous sections it can be seen that the structures experienced the highest performance when C_d was within the range 10 × 106 to 100 × 106 Ns/m and K_d within the range 1 × 106 to 60 × 106 N /m. Hence in order to facilitate comparisons, approximate average values of K_d = 40 × 106 N/m and C_d = 50 × 106 Ns/m, respectively were determined and used in all subsequent cases.

The results showed significant performance of the structures for all damper placements. The high average tip deflection reduction of 10.0% was achieved by the structure with the damper placed in the lower storeys. A slightly higher average tip deflection reduction of 22.8% occurred for the structure with the damper placed in the middle storeys, while the highest efficiency with still relatively high an average reduction of 31.1% was experienced by the structure with the upper storeys damper placement. Clearly the highest average tip deflection reduction, as it was expected, was obtained by the structure with the four and five dampers placement. The results of the tip deflection and tip acceleration of these structures obtained under four earthquake excitations are presented in Table 3.

Table 3: Average Tip deflection and tip acceleration of the damped and undamped structures

	TABAS	**BAM**	**KOBE**	**ELCENTRO**
Deflection(m) Undamped	*0.259*	*0.235*	*0.168*	*0.161*
Deflection(m) Damped	*0.181*	*0.169*	*0.129*	*0.114*
Acceleration(m/s^2) Undamped	*8.76*	*7.21*	*5.96*	*4.87*
Acceleration(m/s^2) Damped	*5.51*	*4.83*	*4.41*	*3.26*

7. CONCLUSIONS AND RECOMMENDATIONS

The main contribution of this research was to establish that seismic mitigation of building structures can be achieved by using dampers embedded within cut outs of the shear wall. This is a novel method of seismic control and the feasibility of this approach has been considered and simply demonstrated for several cases. A strategy for protecting buildings from earthquakes is to limit the tip deflection, which provides an overall assessment of the seismic response of the structure. Different building structures require different damping systems for the best results. However, the present study demonstrated that some trends common for all investigated structures can be observed.To this end, findings of the present study revealed that:

- VE dampers are most effective when placed in the highest storeys.
- Friction dampers are most effective when placed close to regions of maximum inter-storey drift

- Diagonal dampers experienced highest sensitivity to placement and variations in seismic excitations. These dampers achieved the most significant performances under earthquakes, which caused high deflection

This study has shown that it is possible to achieve seismic mitigation, under all earthquake excitations, for all the structures considered in this study, by using appropriate damper types suitably located within the structure.

In order to control the vibration response of the medium and high rise structures during earthquake events, passive dampers as energy absorption devices are mostly used. There have been several studies undertaken to develop a method, which optimizes the use of energy dissipating dampers in vibration control of buildings under earthquake loads. However, the basic theories behind these methods are mostly not supporting each other and in many ways are rather contradicting. Even more, there are numerous types of dampers available commercially as well as numerous types of high-rise buildings with varied properties, which could be treated under seismic loads. In the light of this, there was a great necessity for further development of methods to determine the effective use of dampers in medium and high rise structures.

Despite the availability of sophisticated computer facilities, determining the type of damping devices and their optimal placement and size still remains highly an iterative trial and error process. What makes the problem even more difficult is the uncertainty of seismic inputs as the forces of nature can vary tremendously. The range of the results presented in this study illustrates the complexity of the problem of optimization in the use of damping devices.

The following are suggestions for further research in this area:

- The method of optimizing the location of the dampers within the structure should be further investigated.
- The study should be extended by involving the other toggle configuration proposed by the other authors study.
- Investigation of performances of the damping systems under synthesized excitations with a wide range of frequencies and peak ground accelerations
- Extend the study on use of semi-active damping systems. These are designed to alter the properties to suit the intensity and frequency content of the earthquake, in order to obtained more efficient performance.

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