Mitigating Seismic Response of Shear Wall Structures Using Embedded Dampers

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Abstract

This paper presents a study on mitigating the seismic response of shear wall structures by using dampers strategically located within them. The stiffness of the cut out section of the shear wall is replaced by the stiffness and damping of the device. Friction, Viscoelastic and Hybrid dampers in different configurations and at different locations are used to evaluate the peak deflections and accelerations, under several earthquake records. Results from this conceptual study have demonstrated the feasibility of using these dampers to mitigate the adverse seismic effects of these structures, even under resonant conditions.

Introduction

Under earthquake activity buildings have been known to suffer extensive damage and even total collapse. In order to mitigate the adverse seismic effects on a building, three methods can be identified as being practical and efficient. These are; *structural isolation*, energy absorption at *plastic hinges* and use of *mechanical devices* to provide structural control. In recent years there has been great interest in the use of mechanical energy absorbing devices located within the structure. These devices absorb the energy from the earthquake and reduce the effects on the critical components of the structure. After the earthquake these absorbers can be replaced leaving the building undamaged. There are two types of structural control provided by the addition of mechanical devices; active and passive control. *Active control* requires a power supply to activate the dampers and hence may be undependable during seismic events. On the other hand, *passive energy dissipation systems* have emerged as special devices that are incorporated within the structure to absorb a portion of the input seismic energy. As a result, the energy dissipation demand on primary structural members is often considerably reduced, along with the potential for structural damage.

There are various types of manufactured passive dampers available in the market which use a variety of materials to obtain different levels of stiffness and damping [1]. Some of these include viscoelastic (VE), viscous fluid, friction and metallic yield dampers. These dampers have different dynamic characteristics and so will affect the seismic response of structures differently.

This paper investigates the use of dampers located within cut-outs of shear walls to mitigate seismic response and in particular examines three types of damping mechanisms. The first damping mechanism involves the use of the displacement dependant *friction dampers*, which dissipate energy only when the slip force is reached and exceeded. The second damping mechanism involves the use of the velocity dependant *VE dampers*, which on the other hand, dissipate energy at all levels of deformation and over a broad range of excitation frequencies. The third damping mechanism is a *hybrid system* consisting of friction and VE dampers. The use of both damper types in the hybrid system, can allow effective control of the building's vibration response across a longer excitation time and a greater range of input frequencies.

Damper Models

Finite Element (FE) methods have been employed to model, analyse and investigate the effects of these three types of damping devices on the seismic response of shear wall structures using ABAQUS/Standard Version 6.3. In conjunction with this program, MSC/PATRAN 2003 has been used as the pre-processor for generating the geometry, element mesh, boundary conditions and loading conditions of the model, and as the post-processor for viewing the results of the analysis.

A direct integration dynamic analysis was selected which 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 accelerogram. The dynamic procedure in ABAQUS/Standard uses implicit time integration. To evaluate the effectiveness of the damping systems, the maximum accelerations and displacements at the top level are obtained from the time history analyses and compared with those of the undamped structure.

Modelling of frictional dampers has been in the non-linear range and the initial focus of this research has been on the development of a model which represents the true behaviour of friction dampers. This was treated by modelling the frictional contact between two tubes which slide one inside the other. The extended version of the classical isotropic Coulomb friction model is provided in the computer program ABAQUS for use with all contact analyses.

VE 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. Abbas & Kelly [2] define the stiffness and damping coefficients as follows:

$$k_d = \frac{G'A}{t} \tag{1}$$

$$C_d = \frac{G''A}{ft} \tag{2}$$

where, A is the shear area of the VE material, t is its thickness, f the loading frequency of the VE damper, G' the shear storage modulus, and G'' the shear loss modulus. The following expressions were used to obtain the moduli of the VE material as defined by Abbas & Kelly

$$G' = 16.0 f^{0.51} \gamma^{-0.23} e^{(72.46/Temp)} \tag{3}$$

$$G'' = 18.5 f^{0.51} \gamma^{-0.20} e^{(73.89/Temp)} \tag{4}$$

where, γ, is the shear strain. This model approximates the true behaviour of a VE damper under vibratory loading to within 10% [2], which was considered sufficiently accurate for the purposes of this study. In order to create a computer model, appropriate values of the frequency of loading applied to the damper, the shear strain and the temperature of the VE material have to be selected. In this investigation, the ambient temperature of the VE material was assumed to be 21^0C and the shear strain, γ, was assumed to remain constant at 100%. For the loading frequencies, ω, the first mode of vibration of the structure was used. *The hybrid system* consists of a combination of a VE and a friction damper model in series.

Structural Models

The structural models treated in this conceptual study have been represented by shear walls conveniently modelled in the finite element program using shell elements of designation S4R5. The dimensions of the shear walls were 96 m high, 15 m wide and 0.5 m thick. A total of five different damping systems were considered, these being diagonal friction dampers, diagonal VE dampers, horizontal friction dampers, horizontal VE dampers and a hybrid system consisting of a horizontal friction damper and a diagonal VE damper, as shown in Fig.1.

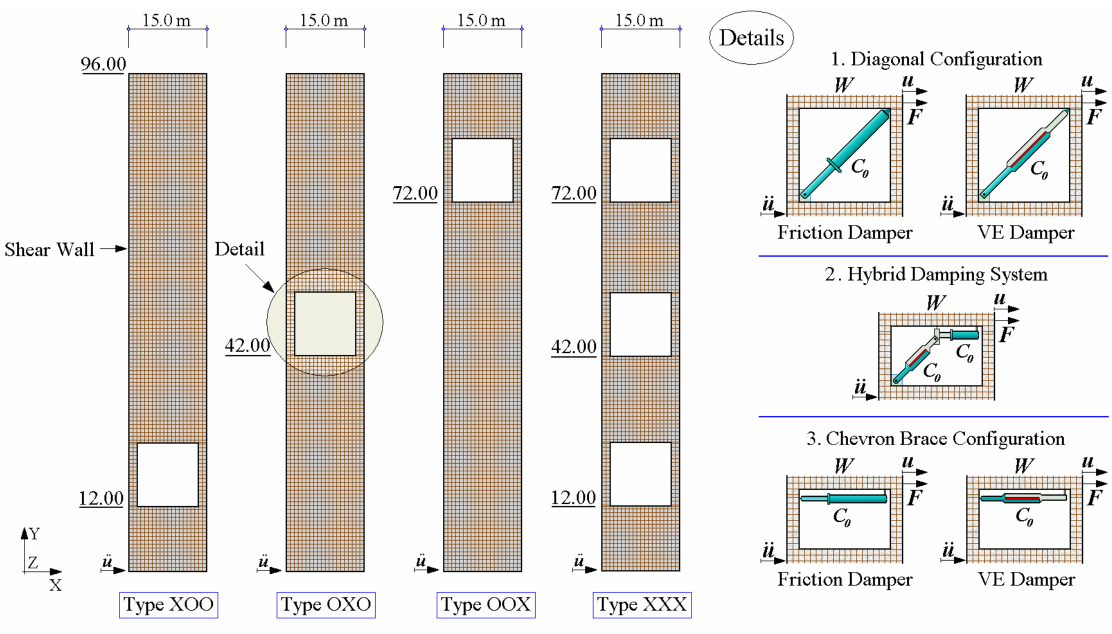

Figure 1: Placement of dampers within shear walls.

Seismic analyses of the shear walls were carried out with one type of damping system at a time. Furthermore, 4 different damper placements were used to study the influence of location on the seismic response of these models. These are designated by xoo, oxo, oox and xxx in which the damper is placed in the lower, middle, upper and all three parts of the structure respectively, as shown in the Fig.1. The undamped structure was also analysed in order to compare results.

The first natural frequency of the shear wall structure, without dampers, was 0.518 Hz and the first natural frequencies of the shear walls with dampers were in the range 0.531 Hz - 0.743 Hz. These values mostly lie within the range of frequencies of dominant modes in all the earthquakes chosen in this investigation (as will be seen later) and hence this study treats resonant vibration of the structural models, at least during the strong motion.

For the shear walls concrete material properties were chosen with a compressive strength, f'_c of 32 MPa, Young's modulus, E_c of 30,000 MPa, which reflect an assessment assuming predominantly elastic response with little wall cracking, Poisson's ratio, υ of 0.2, and density, ρ of 2500 kg/m^3. No internal damping was taken for the concrete since it was assumed small in relation to the damping added by the damping devices. Friction dampers and the frictional component of the hybrid dampers were modelled using structural steel having a Poisson's ratio υ of 0.3 and density, ρ of 7700 kg/m^3.

Models with friction dampers – diagonal configuration

After the preliminary convergence study, the concrete shear wall of the building structure was modelled using 2332 S4R5 shell elements for models types-xoo, oxo, oox, and 1789 S4R5 shell elements for model type-xxx. Details of the friction damper located within the shear wall can be seen in Fig. 2, where a 12.0 m wide by 12.46 m high wall section has been cut out and replaced by a diagonal friction damper. This damper was modelled as a pair of diagonal pipes each with a thickness of 50 mm, and with one pipe placed within the other.

The outer tube having an inner diameter of 200mm and length 14.5m was modelled using 239 S4R5 shell elements while the inner tube having an outer diameter of 198 mm and length

15.0m was modelled using 263 S4R5 shell elements. The contact area in the unloaded state was 16.4 m^2 and the coefficient of friction between the pipes was assumed to be 0.25.

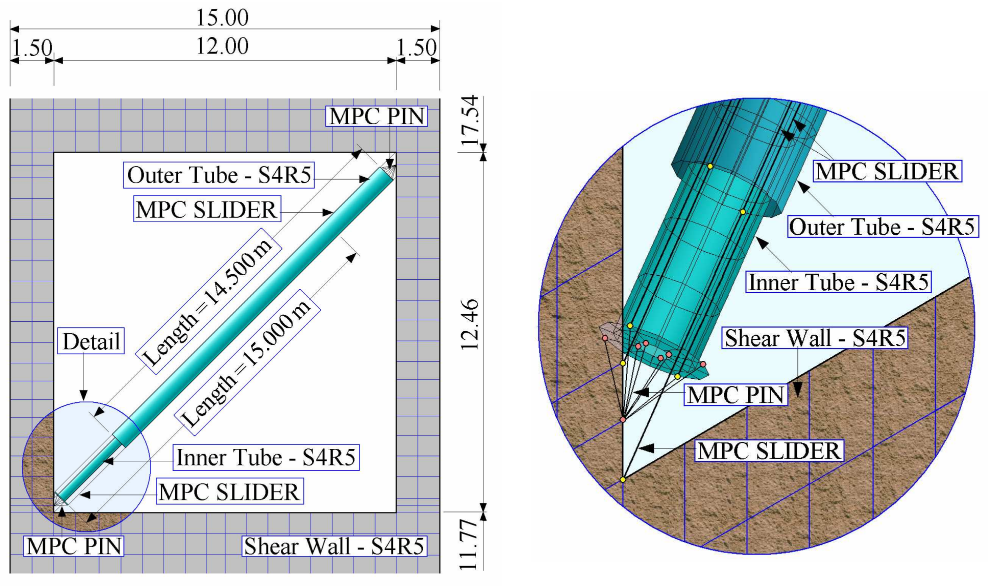

Figure 2: Structural details of friction dampers – diagonal configuration

The connection between each pipe end and the shear wall was modelled using a MPC (Multi-Point Constraint) PIN type connecting element, which provides a pinned joint between two nodes. This MPC makes the displacement of the two nodes equal but allows differential rotations. A MPC SLIDER type connecting element was chosen to ensure frictional sliding between the pipes in the determined direction. This MPC keeps a node on a straight line defined by two other nodes such that the node can move along the line, and the line can also change length.

Models with VE dampers – diagonal configuration

The concrete shear wall was modelled using the same FE mesh, material properties and dimensions as in the previous case. The properties of the VE dampers for structure type xoo were calculated as k_d = 80 x 10^6 N/m and C_d = 109 x 10^6 Ns/m based on double layer dampers in parallel with dimensions of 1,540 mm by 300 mm by 10 mm and the values G' = 861,686 Pa and G" = 1,224,504 Pa. These moduli were calculated using the loading frequency f = 0.531 Hz, which corresponded to the fundamental frequency of this structure. In a similar manner, damping properties of VE dampers located in the structures type- oxo (with f = 0.603 Hz), oox (with f = 0.742 Hz), and xxx (with f = 0.539 Hz) were calculated. The seismic responses of the structures were noticeably close when C_d was within the range 40 x 10^6 to 140 x 10^6 Ns/m and k_d within the range 30 x 10^6 to 120 x 10^6 N /m hence in order to facilitate comparisons, approximate average values of k_d = 100 x 10^6 N/m and C_d = 100 x 10^6 Ns/m, respectively were determined and used in all cases

Models with hybrid damping system

The concrete shear wall was modelled using the same FE mesh, material properties and dimensions as before. The only difference was in the size of the cut out which was reduced to 12.0 m wide by 8.0 m high.

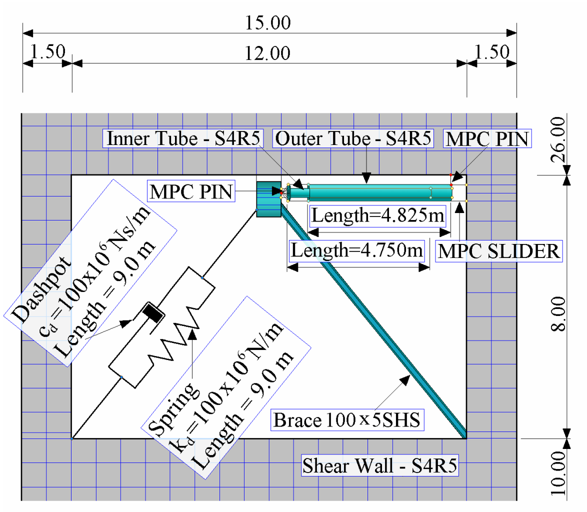

Figure 3: Structural details of hybrid damping system.

The friction component of the hybrid damping system shown in Fig.3 was modelled as a pair of horizontal pipes, with one pipe placed within the other. The material properties and dimensions, except for length, were the same as in the diagonal friction damper. The contact area in the unloaded state was 5.4 m^2. The direction of frictional sliding was determined by SLIDER and PIN type MPCs.

The VE part of the hybrid damping system which represented both spring and dashpot elements was oriented with one end attached to a steel holder placed in the middle of the upper edge of the cut out, and the other end attached to the lower left-hand corner of the cut out. This oriented the damper at 40^0 to the vertical while its length was 9.0 m. Damping and stiffness were kept the same as in the diagonal VE dampers.

Models with friction dampers – chevron brace configuration

The concrete shear wall and cut out were as in the previous (hybrid) case. The parameters of the chevron brace friction damper are illustrated in Fig.4. The contact area in the unloaded state was 13.3 m^2. The direction of frictional sliding was determined by SLIDER and PIN type MPCs, as before.

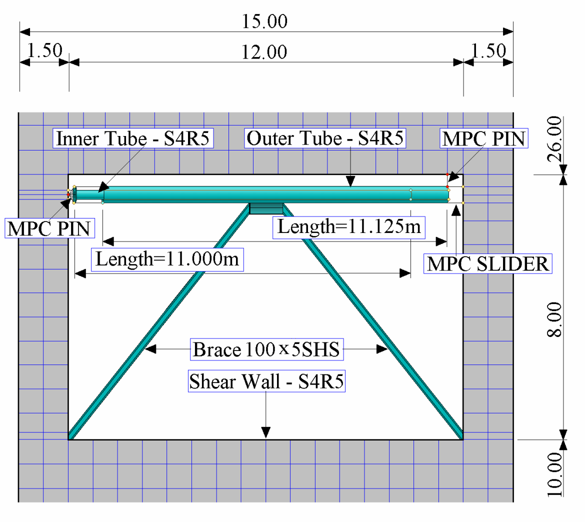

Figure 4: Structural details of friction damper – chevron brace configuration.

Models with VE dampers – chevron brace configuration

The concrete shear wall and cut out were as in the cases of hybrid and chevron brace friction damping systems. The damper placed within the shear wall was oriented horizontally in the upper part of the cut out, attached at one end directly to the left side of the shear wall and attached at the other end to the upper edge of the shear wall via an MPC PIN connection.

Earthquake records

In general, earthquakes have different properties such as peak acceleration, duration of strong motion and ranges of dominant frequencies and therefore have different influences on the structure. In order to ensure that the chosen mitigation procedure is effective under different types of excitations, five, well-known earthquakes records were used in this study. These were all applied for the first 20s of their duration. For more consistent comparison, all earthquake records were scaled to a peak acceleration of 0.1g. Duration of the strong motion and range of dominant frequencies were kept unchanged and were evaluated by Welch's method [3] with the computer program MATLAB Version 6.5. The selected earthquake records and their features are as follow: El Centro(1940) with duration of strong motion in the range of 1.5-5.5 secs and dominant frequencies in the range 0.39-6.39 Hz, Hachinohe(1994) with duration of strong motion in the range of 3.5-7.5 secs and dominant frequency in the range 0.19-2.19 Hz, Kobe(1995) with duration of strong motion in the range of 7.5-12.5 secs and dominant frequencies in the range 0.29-1.12 Hz, Northridge(1994) with duration of strong motion in the range of 3.5-8.0 secs and dominant frequencies in the range 0.14-1.07 Hz and San Fernando(1971) with duration of strong motion in the range of 4.5-9.5 secs and corresponding frequencies in the range 0.58-4.39 Hz . The properties of the San Fernando earthquake, however, are such that it was difficult to identify the dominant frequencies.

Results

There are various ways of assessing seismic response but computation of tip deflection is a reasonable measure of the overall effect of the earthquake. Working back from tip deflection to equivalent base shear and moment is one way of 'averaging out' the seismic effects of varying accelerations up the wall. Hence any reduction is a worthwhile in overall seismic design force. The results show that the value of reduction is dependent on the complex characteristics of the time histories used for assessment. Hence the benefits can only be legitimately assessed if the analysis is carried out for suite of time histories.

The reductions in tip deflection and tip acceleration obtained with all damper types, configurations and at all locations for each of the five earthquake records compared with that of the undamped structure are presented bellow.

Table 1 shows the tip deflections and acceleration of the undamped structure under all five earthquake excitations.

Table1

Tip deflection and tip acceleration of the undamped structure.

	El Centro	Hachinohe	Kobe	Northridge	S.Fernando
Deflection(m)	0.161	0.356	0.168	0.143	0.141
Acceleration(m/s^2)	4.87	5.33	5.96	5.57	4.42

Fig.5 illustrates the average percentage reduction in the peak values of the tip deflections experienced by all the structural models compared with that of the undamped structure. All five types of damping systems performed well. Overall, the highest reduction was achieved by models with hybrid damping systems with an average reduction of 22.2%. Surprisingly, the second highest reduction was achieved by models with chevron brace friction dampers, followed by models with diagonal friction and VE dampers, which each showed relatively similar performance. Finally, the lowest performance was recorded for models with chevron brace VE dampers, with an overall reduction of 12.3%.

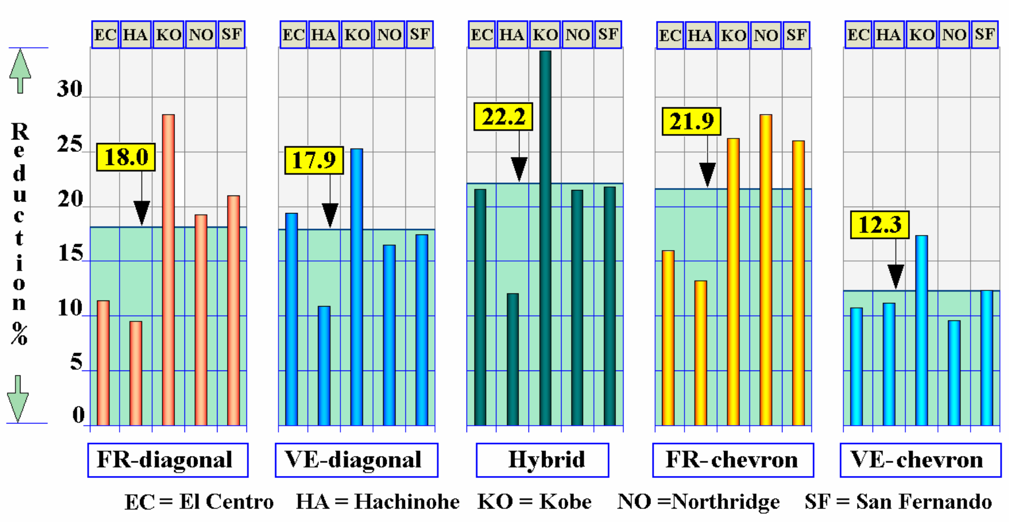

Figure 5: Average reduction in tip deflection for all five types of damping systems.

Fig.6 illustrates the average percentage tip deflection reduction of the models with respect to the damper locations.

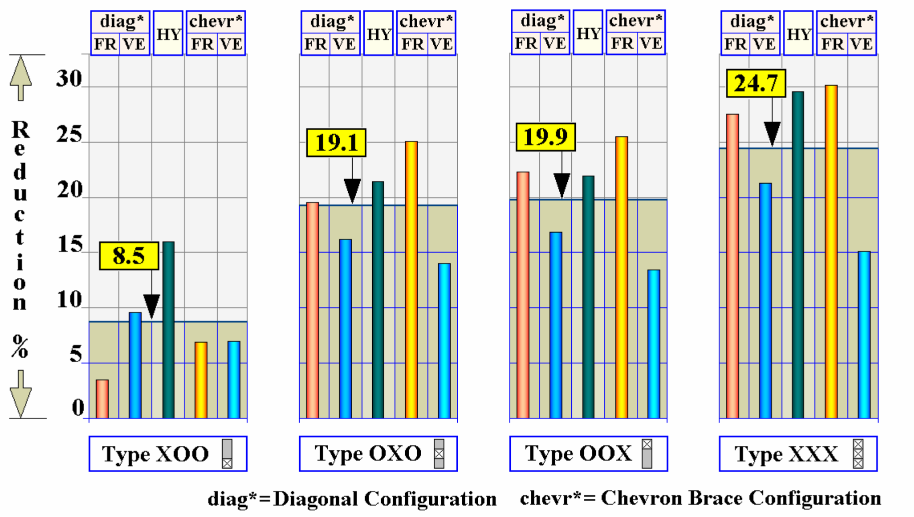

Figure 6: Average tip deflection reductions (under all five earthquakes) for different damper location.

The best performance was achieved in structure type-xxx, with an overall reduction of 24.7% with dampers in all three parts of the model. The second best performance with an overall reduction of 19.9% was achieved for model type-oox with dampers placed in the upper part of the structure, following by an overall reduction of 19.1% for model type-oxo with dampers placed in the middle part of the structure. Finally an overall reduction of 8.5% was obtained for type-xoo representing dampers placed in the lower part of the model which was considerably less than that obtained in other cases.

The efficiency of the damping systems under a variety of earthquake loadings has been also evaluated and results could be observed from Fig.7.

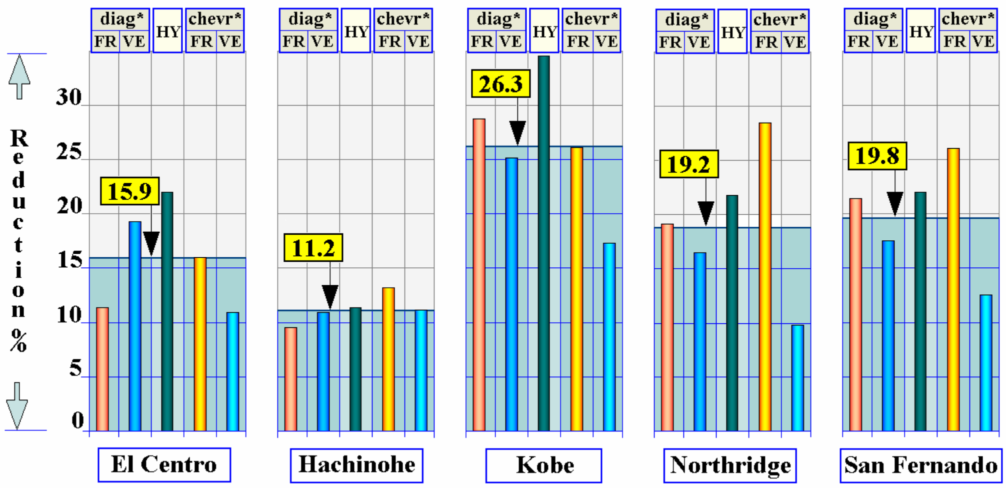

Figure 7: Average tip deflection reductions (for all five types of damping systems) under each earthquake.

It can be seen that the greatest average reduction in tip deflection was 26.3 %, under the Kobe earthquake, which was characterised by a narrow dominant frequency range (0.29-1.12Hz). The second best average reduction of 19.8% was displayed under the San Fernando earthquake, which, in contrast to the Kobe earthquake, had a wide band of dominant frequencies (0.58-4.39 Hz). The performance of the models under the Northridge earthquake, which had a narrow dominant frequency range (0.14-1.07 Hz), was slightly less with an average reduction of 19.2%. In the case of the El Centro earthquake record, which displays a wide band of dominant frequencies (0.39-6.39Hz), the efficiency of the models was slightly lower with an average reduction of 15.9%. The lowest performance of 11.2% was achieved under the Hachinohe earthquake record, which had a moderate dominant frequency range (0.19-2.19Hz).

The primary objective of this study was to investigate the tip deflection of the structure. In addition also the percentage reductions in the peak values of the tip accelerations were studied and the results are presented in Figs.8-10.

Fig.8 shows that all types of damping systems produced good results. Overall, the highest reduction was achieved by models with diagonal friction damping systems, with an average reduction of 42.8%. The second best were models with diagonal VE dampers, followed by models with hybrid damping system and models with the chevron brace VE damper. Finally, lowest performance was for models with chevron brace friction dampers, with an overall reduction of 18.1%.

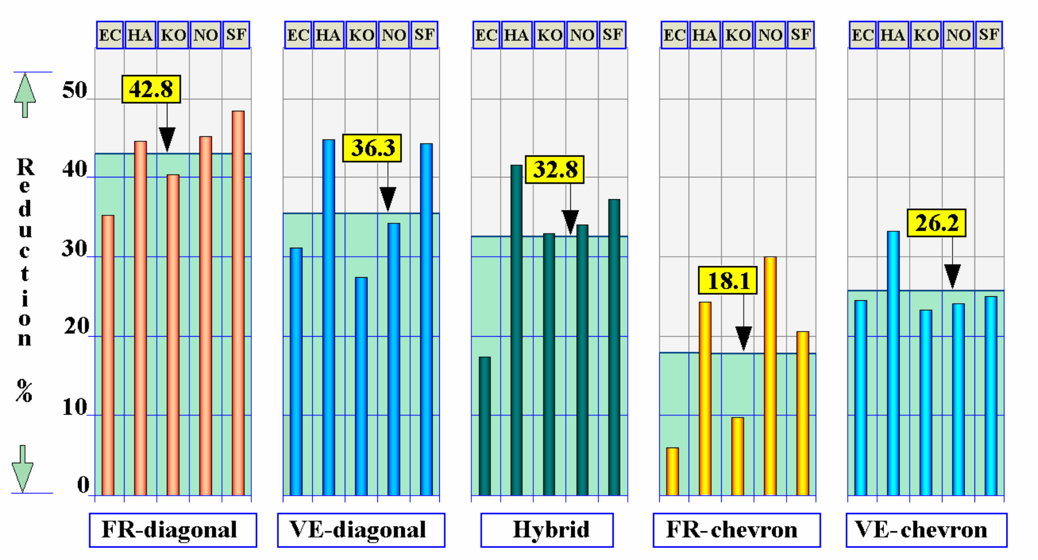

Figure 8: Average reductions in tip acceleration for all five types of damping systems.

In terms of damper placement, the best performance, with an overall reduction of 42.5% was achieved in type-xoo representing the model with dampers placed in the lower part of the structure (Fig.9), while type-xxx, with dampers in the all three parts of the structure, displayed a reduction of 36.1%. A lower overall reduction of 27.1% was achieved by type-oxo with the dampers placed in the middle part of the structure, and lastly the lowest performance was achieved by type-oox with the dampers placed in the upper part of the structure, with an overall reduction of 16.4%.

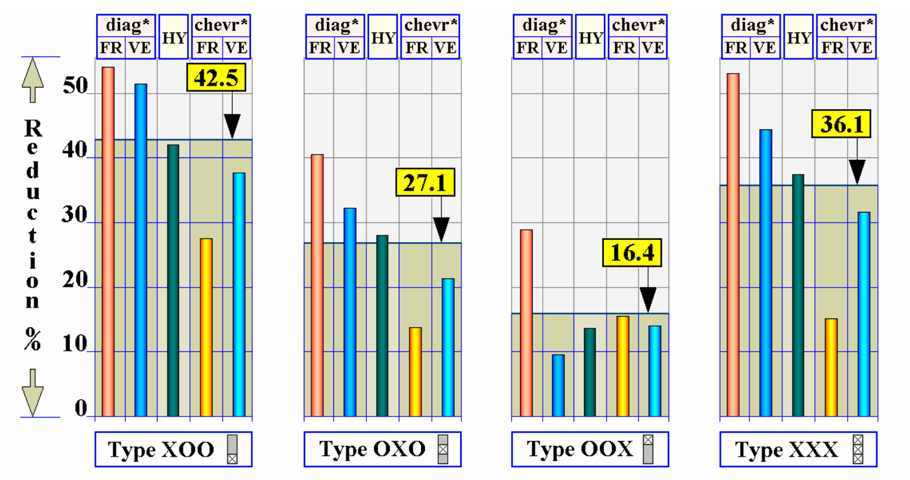

Figure 9: Average tip acceleration reductions (under all five earthquakes) for different damper location.

The efficiency of the damping systems for reducing tip acceleration under a variety of earthquake loading is illustrated in Fig.10.

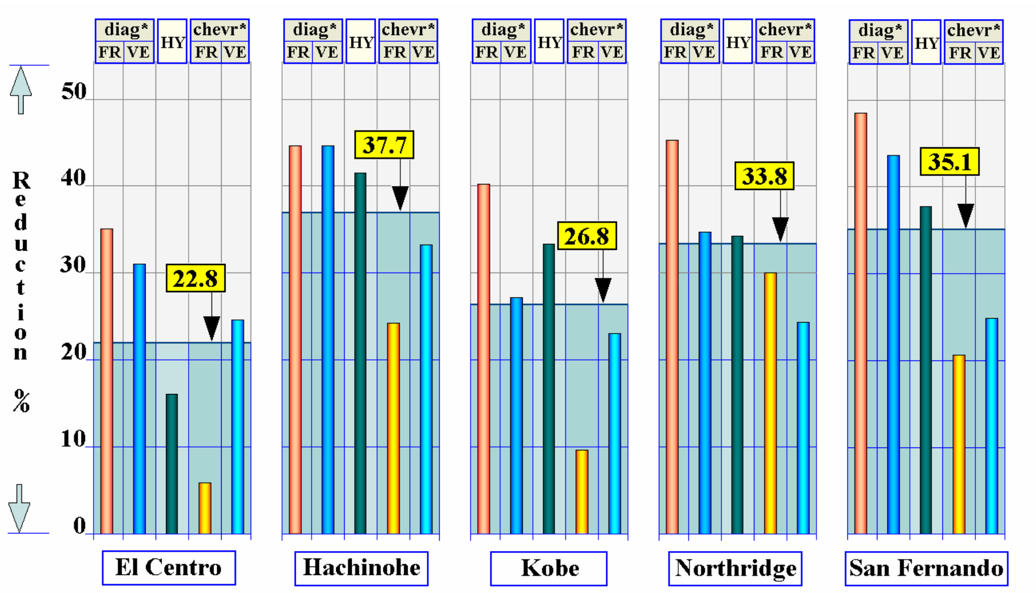

Figure 10: Average tip acceleration reductions (for all five types of damping system) under each earthquake.

The best performance was displayed under Hachinohe earthquake with an overall reduction of 37.7% and slightly lower reduction of 35.1% under the San Fernando earthquake. The overall reduction recorded for the Northridge earthquake was lower with an average of 33.8%, followed by 26.8% for the Kobe earthquake and finally the lowest reduction with average value of 22.8% was recorded under the El Centro earthquake.

This study has demonstrated the feasibility of using embedded dampers to mitigate the adverse seismic response of shear wall structures. As the natural frequencies of these structural models were mostly within the frequency range of the dominant modes of the earthquakes, this study treated resonant vibration. It was probably due to this reason that there were no particular trends in the responses under the different earthquakes. The outcome of this conceptual study might find application in any structural system, especially high rise building, subject to any periodic input motion as for example wind buffeting.

Conclusion

This conceptual study investigated the use of three types of damping mechanisms, viz, VE, friction, and hybrid (friction-VE) dampers, located within cut outs of shear walls, to mitigate the seismic response of shear wall structures. These structural systems have been modelled and analysed under five different earthquakes, using finite element techniques. The effects of damper type, configuration and location on the seismic response were studied. The results of this investigation confirmed that substantial reductions in acceleration and deflection of the structure could be achieved by all three types of dampers in all configurations and at all locations. However, responses under earthquakes with varying frequency content and strong motion duration have yielded a wide range of results and some interesting features.

In terms of reduction in the tip deflection, the best performance was observed when dampers were placed in the upper level, while greatest reduction in the peak values of tip acceleration was achieved when dampers were placed in the lower level. VE dampers performed better than friction dampers in the lower and middle parts of the structures, while friction dampers performed better in the upper parts of the structure and throughout. Hybrid dampers were overall the most efficient and also had the most stable performance.

In this conceptual study, the natural frequencies of most of the structural models (with cut outs at different location) were within the frequency range of the dominant modes of the earthquakes. Hence, this study encountered resonant structural vibration, in most cases during the strong motion, and has demonstrated the possibility of mitigating seismic response of structures by an appropriately embedded damping systems. Research findings may find applications in both new designs and in retrofitting existing structures if cut outs can be made across several storeys. Since paper submission, the study has continued and has treated frame shear wall structures and additional configurations of damping systems. Results have shown the feasibility of this technique in seismic mitigation of building structures and provided information for optimising this mitigation.

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