ENHANCING THE SEISMIC PERFORMANCE OF RC COUPLED WALL HIGH-RISE BUILDINGS WITH VISCOELASTIC COUPLING DAMPERS

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SUMMARY:
A new damping system for high-rise buildings, the viscoelastic Coupling Damper (VCD), has been developed at the University of Toronto. VCDs are introduced in lieu of coupling beams in reinforced concrete (RC) coupled wall buildings, adding distributed damping in all lateral modes of vibration. In the event of a large earthquake, capacity designed fuse elements activate, preventing damage to adjacent structural elements. Activated fuses can then be inspected and quickly repaired or replaced.

A conventional RC coupled wall building is compared to an alternative design incorporating VCDs. Nonlinear time history analysis was carried out using suites of service level, design basis and maximum credible earthquakes. Results highlight the improved performance of VCDs over diagonally reinforced coupling beams at the SLE hazard level. Equivalent performance was also achieved at the DBE and MCE levels. Losses associated with structural damage are expected to be lower for all three levels of seismic hazard.

Keywords: Viscoelastic Coupling Damper, Damping, High-rise Buildings, Coupling Beams, Shear Walls

1. INTRODUCTION

Reinforced concrete (RC) coupled walls are one of the most widely used lateral load resisting systems for high-rise buildings. During large seismic events, plastic hinges develop in the coupling beams and at the base of each wall, resulting in the formation of a plastic mechanism. In areas of moderate to high seismic hazard, specially detailed diagonal reinforcement is provided in order to increase the ductility and energy-dissipating properties of the RC coupling beams (Fig. 1.1 b). The complexity of detailing required in these beams results in increased construction time and costs. Another significant drawback associated with this type of construction is the extensive damage that is likely to be sustained following a major seismic event. Economic losses associated with repair or replacement of damaged coupling beams can be significant, as was the case for many tall building owners after the 2010 Conception earthquake in Chile (Fig. 1.1 c). In some cases the extent of damage may be so great that it becomes more economical to decommission the building.

An alternative design solution for RC coupled wall systems using the Viscoelastic Coupling Damper (VCD) (US Patent US7987639, Montgomery 2011) offers improved seismic performance and structural resilience. VCDs are substituted in lieu of coupling beams in a coupled wall system. In this configuration, VCDs provide distributed viscous damping to the structure as well as coupling of the walls during severe wind storms and small to moderate seismic events. In regions of high seismic hazard, these dampers can be capacity designed using a force-limiting “fuse” detail.

This paper presents the results of a comparative study on the seismic performance of two prototype coupled wall structures located in Los Angeles, CA. The reference structure is a 42-storey case study building designed by Magnusson Klemencic Associates for the Pacific Earthquake Engineering Research Center (PEER) Tall Buildings Initiative (PEER 2011). An alternative design uses VCDs in lieu of diagonally reinforced coupling beams at each floor level. The results of nonlinear time history analyses comparing the performance of the structures at three levels of seismic hazard are presented. Expected losses due to damage at the different hazard levels are also discussed.

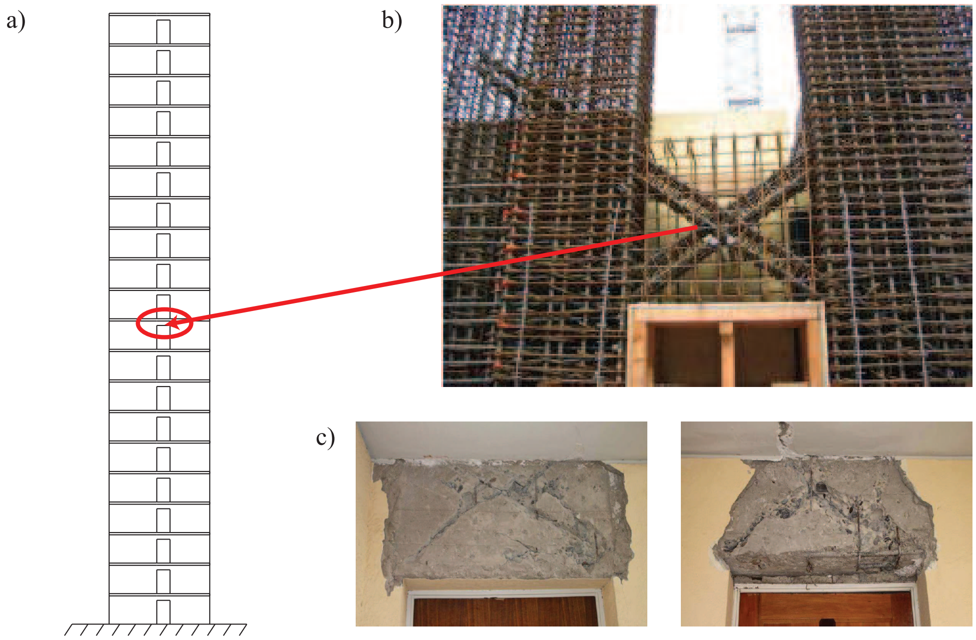

Figure 1.1 a) Schematic of RC coupled wall structure, b) Typical reinforcing detail for diagonally reinforced coupling beams (Wallace 2006), c) Coupling beam damage in recently-constructed high-rise condominiums after Conception 2010 (LATBSDC 2010)

2. VISCOELASTIC COUPLING DAMPER (VCD)

A new viscoelastic damping device for high-rise buildings has been developed at the University of Toronto. The VCD consists of multiple layers of viscoelastic material, placed between layers of steel plate which are anchored at alternating ends to the coupled RC walls using a number of different connection details (Fig. 2.1). These VCD elements replace some of the RC coupling beams in coupled wall buildings to provide supplemental distributed damping. In this configuration, the viscoelastic (VE) material undergoes shear deformations due to the relative motion of the coupled walls under lateral loading. As it deforms in shear, the VE material develops both a velocity-dependent viscous force and a displacement-dependent elastic restoring force, which has the effect of adding damping and stiffness to the system.

In regions of high seismicity, a ductile “fuse” mechanism can be added in series with the VE material. In the event of a large earthquake, the fuse yields or activates, limiting the forces transmitted to the adjacent RC walls and preventing tearing in the VE material due to large shear deformations. The VCD is then able to safely undergo large shear deformations as a combination of VE material deformations and fuse element nonlinear deformations. There are many structural details which can be used to form a reliable ductile fuse mechanism, such as reduced beam sections (RBS) (Fig. 2.1), a shear-critical fuse, a slip-critical friction fuse, or a force-limiting anchorage detail.

Figure 2.2 shows the hysteretic response characteristics of the VCD. Under wind and low level earthquakes loads, the connecting elements remain elastic and effectively damage-less as shear deformation occurs primarily in the VE material (Fig. 2.2a). Under extreme earthquake loading, the fuse mechanism forms and the VCD exhibits visco-elasto-plastic behaviour (Fig. 2.2b). In the extreme loading scenario the majority of shear deformations occur in the fuse element(s). The VCDs are easily inspected following a major seismic event, and can be readily repaired or replaced.

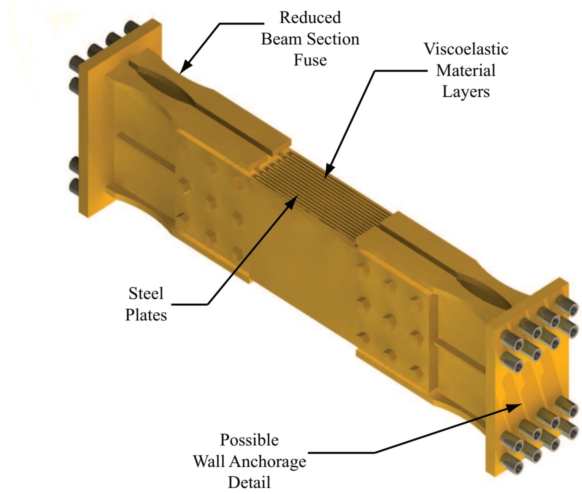

Figure 2.1 Viscoelastic Coupling Damper (VCD)

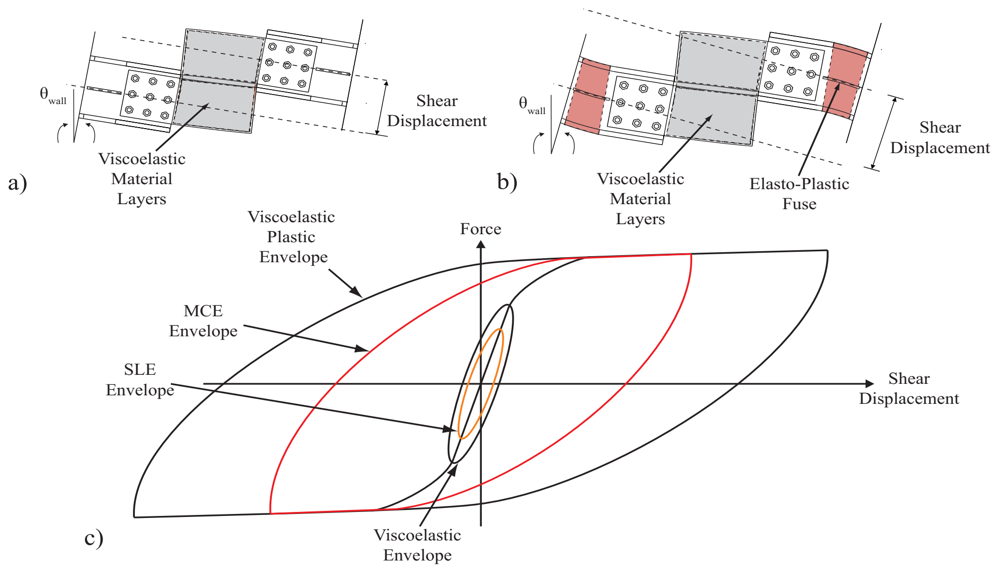

Figure 2.2 a) Viscoelastic deformed shape, b) Viscoelasto-plastic deformed shape, c) Design hysteresis envelopes

3. CASE STUDY BUILDING

The PEER Tall Buildings Initiative (TBI) was founded in 2006 in response to a lack of available guidelines for performance-based design of tall buildings. As part of this research and development study, a high rise coupled RC corewall structure was designed by Magnusson Klemencic Associates. Three different versions on the building were designed in order to evaluate and improve on existing design guidelines. The reference structure for the present study is based on the prototype building designed according to the performance based design criteria published by the Los Angeles Tall

Buildings Structural Design Council (LATBSDC 2008). This structure was optimized for seismic performance following state-of-the-art design criteria.

The reference structure is a 42-storey hotel consisting of an RC core with diagonally-reinforced coupling beams, and a gravity load resisting system comprised of flat slabs supported on perimeter RC columns. A 3D nonlinear analysis model was built using CSI Perform-3D (CSI 2007). The model included the RC core, ground floor and basement slabs, and foundation walls (Fig. 3.1). Structural geometry and details, as well as material properties and gravity loads are consistent with those used the study by PEER (2011).

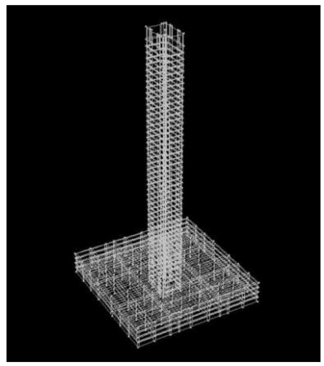

Figure 3.1 Perform-3D model of prototype building

4. ALTERNATIVE DESIGN

An alternative design using VCD links was developed for the prototype structure. At every floor level four of the diagonally reinforced coupling beams were replaced by two VCD links in parallel (two in the north-south direction, two in the east-west direction). A total of 172 coupling beams were replaced in the structure. The link elements were designed to have the same length as the diagonally reinforced coupling beams (1300 mm in the east-west direction, and 1600 mm in the north-south direction). The VCD design includes 30 layers of ISD-111H VE material 350 mm (l) x 560 mm (d) x 5 mm (t), in series with a shear-critical fuse element (Fig. 4.1).

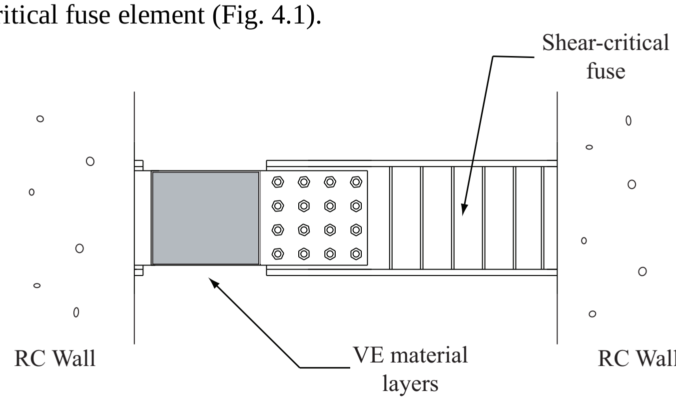

Figure 4.1 Shear force limiting VCD

In a coupled core wall configuration, the shear-critical fuse elements are designed to dissipate energy in a manner similar to that of link elements in eccentrically braced steel frames (EBF). Research has shown that short steel links designed and detailed to yield in shear possess excellent ductility and energy-absorption properties (Engelhardt & Popov, 1992). In the case of this prototype structure, a shear-critical fuse detail was selected because of the relatively short span-to-depth ratio of the coupling beams, in addition to the stable hysteretic behaviour of shear fuses.

5. VCD MODELLING TECHNIQUES

Kasai (2002) developed a model to capture the behaviour of a visco-elasto-plastic damping device. The same model, oriented in the direction of shear deformation at the midspan of a rigid beam element, can be used to capture the response of the VCD (Fig. 5.1a). An equivalent Kelvin-Voigt model, consisting of a spring and a dashpot in series, is used to capture the viscoelastic force-displacement response of the damper (Fig. 5.1b). A rigid-plastic shear hinge, with activation force V_{fuse}, is placed in series with the Kelvin-Voigt model to account for the response of the force-limiting fuse (Fig. 5.1c).

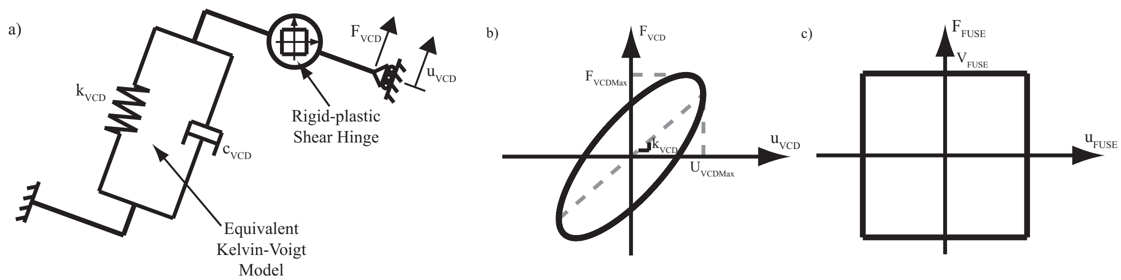

Figure 5.1 a) Schematic of VCD model, b) Viscoelastic VCD hysteresis, c) Rigid-plastic shear hinge hysteresis

The force-displacement response of the VCD is expressed as:

$$F_{VCD}(t) = k_{VCD} u_{VCD}(t) + c_{VCD} \dot{u}_{VCD}(t) \tag{5.1}$$

where F_{VCD}, u_{VCD}, and $\dot{u}_{VCD}(t)$ are the shear force, shear displacement, and shear velocity, respectively, in the damper at time t, and k_{VCD} and c_{VCD} are the equivalent stiffness and damping coefficients of the damper. Because the stiffness and damping coefficients of the VE material vary with temperature, strain amplitude, and frequency of excitation, upper and lower bound values should be used to establish a design envelope for the VCD. For the purpose of this comparative study, a set of average properties of the VE material during a large seismic event were determined. An average VE material temperature of 24℃ and an average VE material strain of 200 per cent (10 mm) were assumed for all dampers. It was also assumed that the dampers would be excited primarily in the fundamental period of vibration of the structure in each direction. The properties used in the two VCD designs are listed in Table 5.1.

Table 5.1 VCD damper properties for alternative design

Direction	Length (mm)	k_{VCD} (kN/mm)	c_{VCD} (kNs/mm)	V_{fuse} (kN)
North-South	1600	156.8	37.4	2,150
East-West	1300	155.9	61.4	2,150

6. GROUND MOTION SELECTION AND SCALING

Seven pairs of historic ground motion records were selected, as listed in Table 6.1. The ground motions were scaled in accordance with the procedure outlined in ASCE 7 to match the 5% damped site specific spectra for three different hazard levels (PEER 2011). Nonlinear time history analysis was carried out at the SLE, DBE, and MCE hazard levels, based on return periods of 43, 475, and 2475 years, respectively. Analysis results from three of the ground motion pairs are presented in this paper.

Table 6.1 Ground motion records used in nonlinear time history analysis

Record Name	Region	Station	Magnitude	R (km)
Superstition Hills	U.S.A.	Parachute Test Site	6.54	0.9
Denali	Alaska	Pump Station #9	7.90	54.8
Northridge	U.S.A.	Sylmar Converter Station	6.69	5.3
Kocaeli	Turkey	Izmit	7.51	7.2
Landers	U.S.A.	Yermo	7.28	23.6
Duzce	Turkey	Duzce	7.14	6.6
Loma Prieta	U.S.A.	Saratoga Aloha	6.93	8.5

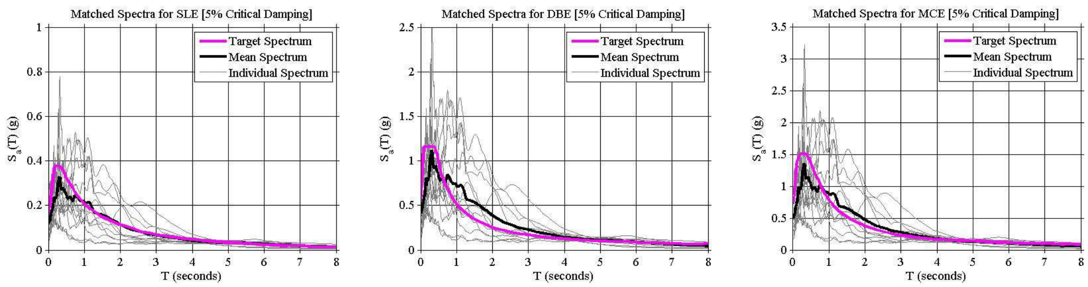

Figure 6.1 Scaled site specific spectra

7. BENEFITS OF DAMPING FOR THE WIND RESPONSE OF HIGH-RISE BUILDINGS

Considering the very low levels of inherent damping in tall buildings (CTBUH 2008), small amounts of distributed viscous damping can have a significant effect on the dynamic wind response, the dynamic wind response, u_d (accelerations, velocities dynamic displacements or loads), is reduced as a function of inherent damping, ξ (ASCE 2010, NBCC 2010):

$$u_d = f(1/\sqrt{\xi}) \tag{7.1}$$

Using ETABS, modal damping added from the VCDs was calculated to be above 2.5% in the first three modes of vibration. Assuming the level of inherent damping is 1.0%, the reduction in vibration response (accelerations, velocities and dynamic displacements) resulting from added damping of 2.5% in the first three modes of vibration corresponds to roughly 47%.

8. NONLINEAR ANALYSIS MODELS

Nonlinear properties were assigned to the core wall flexural behaviour and the shear behaviour of the diagonally reinforced coupling beams, which were expected to undergo inelastic deformations under seismic loading. The core wall shear behaviour, as well as the slab diaphragms and foundation walls were assigned elastic properties since these elements were expected to remain elastic even under the most severe seismic loading.

Nonlinear models of the reference structure and the alternative design were created using Perform-3D. Only the lateral load resisting system was represented in the model since studies have shown that including the gravity system does not have a significant effect on seismic response (PEER 2011). Rigid diaphragms were assigned to the core wall elements at each floor and seismic mass was assigned at each floor above the ground level. The ground floor and basement slabs were modelled using finite element meshes with a reduction factor of 0.25 to account for concrete cracking. Boundary conditions were modelled using pin supports at the level of the top of the foundation mat. Soil-structure interaction was not accounted for in the model. Viscous damping was assigned 2.5 per cent Rayleigh damping at periods of 1 and 5 seconds for all analyses.

The combined axial and flexural response of the core walls was modelled using nonlinear fibre shear wall elements. The wall thickness was reduced to account for the effect of spalling and all concrete was defined as confined. The shear behaviour of the walls was defined using a linear elastic force-deformation relation and an effective shear modulus of $0.2E_c$, where E_c is the expected Young's modulus of the concrete. Shear-flexure interaction is not accounted for in Perform-3D. Basement walls were modelled as elastic shear wall elements with an assumed thickness of 400 mm and a reduction factor of 0.8 to account for concrete cracking. Diagonally reinforced coupling beams were modelled following recommendations from Naish et al. (2009). Each beam was modelled as an elastic beam element with an effective flexural stiffness of $0.15E_cI_g$ and a nonlinear shear displacement-based hinge element located at midspan.

In order to capture the response of the VCD in Perform-3D, a viscous bar element, consisting of a spring and dashpot in series, was used to create an effective Kelvin-Voigt model. This was done by assigning a very large stiffness (≈infinite) to the spring and placing a spring element with the effective damper stiffness in series with the viscous bar element. A rigid beam element with an equivalent Kelvin-Voigt element oriented in the direction of shear deformation at midspan was used to couple the wall elements in the alternative building model. Because viscous bar elements must be assigned a length in Perform-3D, rigid beam elements were used to simulate rigid offsets connecting the VCDs to the shear wall elements. A rigid-plastic shear hinge was added in series with the damper to represent the shear-critical fuse (See Fig. 5.1a).

9. NONLINEAR ANALYSIS RESULTS

As shown in Figures 9.1and 9.2, a significant reduction in inter-storey drift was observed the SLE hazard level in both East-West and North-South directions because of the added damping provided in the VCD structure. A less significant reduction in inter-storey drift was noted at the DBE and MCE levels since both the RC coupling beams and VCDs deform plastically at these levels of seismic loading.

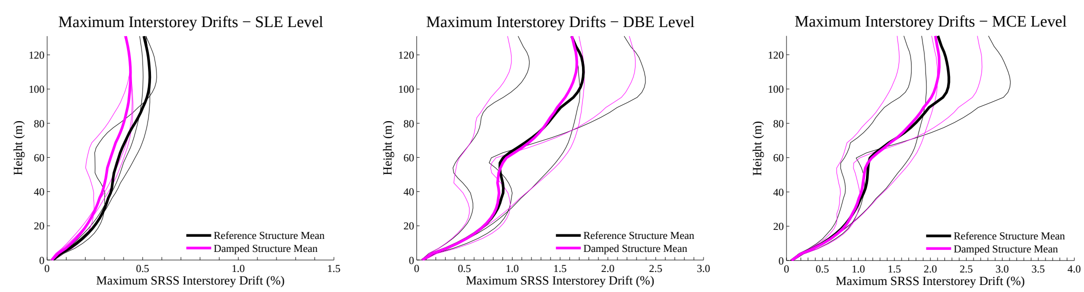

Figure 9.1 Maximum Interstorey Drifts – East-West Direction

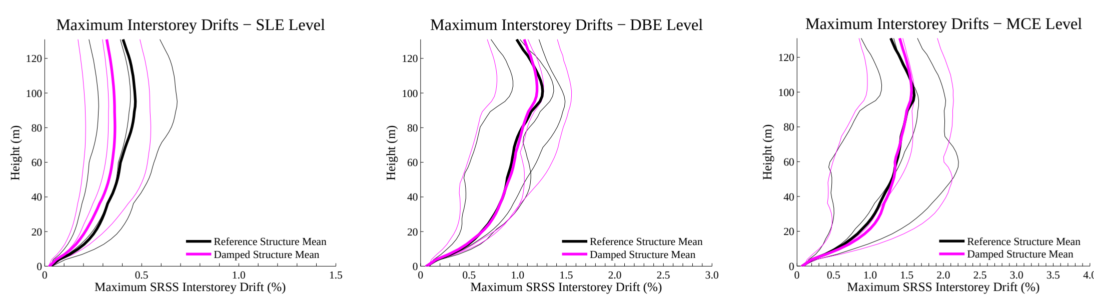

Figure 9.2 Maximum Interstorey Drifts – North-South Direction

Figures 9.3 and 9.4 show storey shear reduction in both directions in the SLE hazard level and comparable storey shears at the DBE and MCE levels.

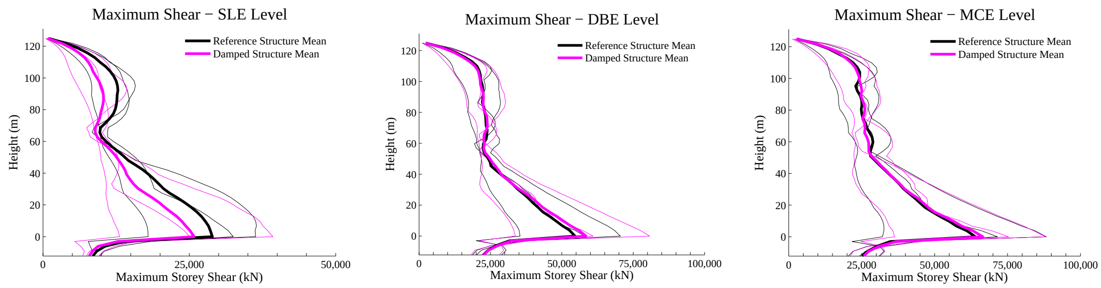

Figure 9.3 Maximum Storey Shear – East-West Direction

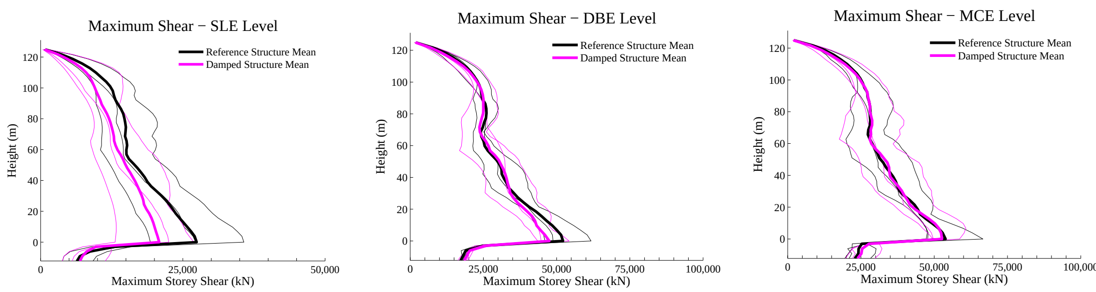

Figure 9.4 Maximum Storey Shear – North-South Direction

As shown in Figures 9.5and 9.6, there is a slight reduction in peak floor accelerations at all hazard levels in both directions, because of the added damping in the VCD structure. The results from both structures are very similar at the DBE and MCE levels, because both the coupling beams and dampers are responding primarily plastically.

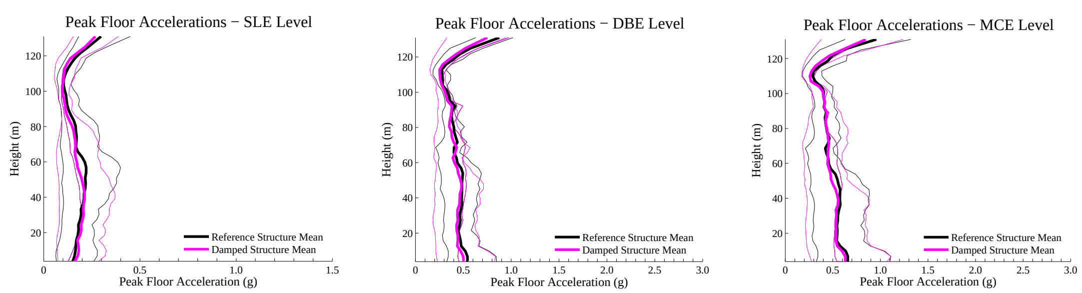

Figure 9.5 Maximum Storey Acceleration – East-West Direction

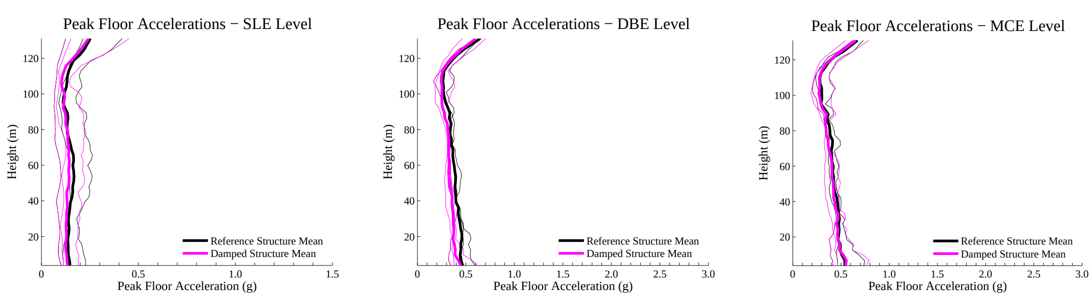

Figure 9.6 Maximum Storey Accelerations – North-South Direction

Maximum coupling beam rotations on the South core wall resulting from the Loma Prieta record scaled to the DBE and MCE hazard levels are plotted in Fig. 9.7. The need for repair of coupling beam elements is expected to occur beyond a rotation of 0.02 radians (PEER 2010). As indicated in the figure, 14 coupling beams reached this level of rotation during the DBE level event. At the MCE level, a total of 37 coupling beams would require repair.

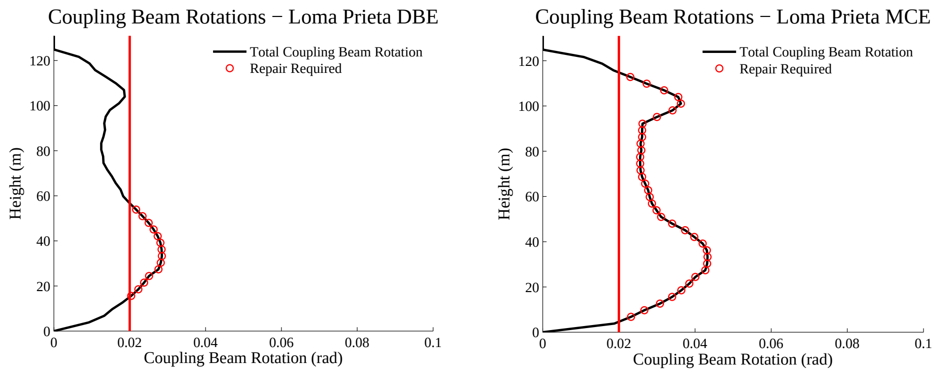

Figure 9.7 Peak Coupling Beam Rotations – Loma Prieta

The VCD is assumed to have permanent damage requiring its replacement in the event that the VE material is deformed beyond an allowable strain of 400%, or when excessive plastic deformations are sustained by the yielding steel fuse element. As intended in the design of the VCD, it was confirmed that the VE material strains did not exceed 200% in all of the analyses since the steel fuse elements were designed to activate at a force corresponding to a shear deformation of 200% in the VE material. Based on extensive experimental data on the response of steel shear yielding link elements (Mansour 2010), it was assumed that replacement would be required if the plastic rotation in the yielding fuse element reached a value of 0.04 rad.

Figure 9.8 shows the peak shear fuse plastic rotations on the South core wall resulting from the Loma Prieta record scaled to the DBE and MCE hazard levels. As shown in the figure, none of the VCDs would require repair following the DBE level event and only 16 VCDs would require repair or replacement at the MCE level.

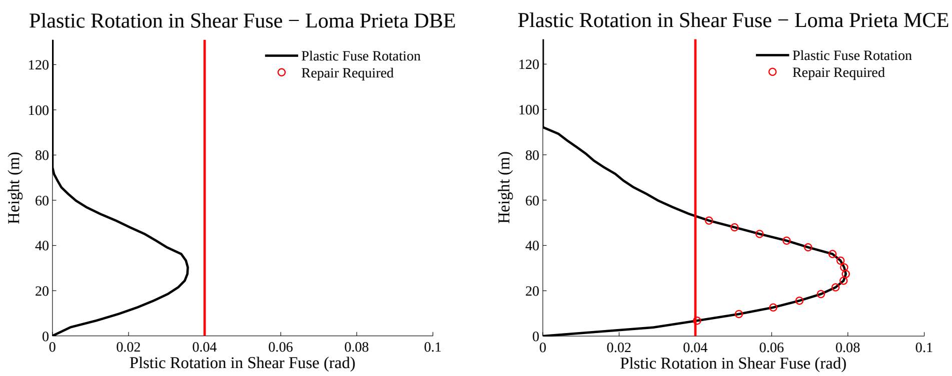

Figure 9.8 Peak Shear Fuse Plastic Rotations – Loma Prieta

10. CONCLUSION

In this paper the performance of a 42-storey case study building designed by Magnusson Klemencic Associates, in accordance with state-of-the-art performance-based design guidelines, was investigated and compared with an alternative design using Viscous Coupling Dampers.

The added damping provided by the VE material effectively reduced the service level earthquake response of the alternative design (drifts, accelerations and storey shears) when compared to that of the reference structure. Nonlinear time history analysis results indicate that comparable performance (drifts, accelerations and storey shears) was achieved in the alternative design at the maximum credible and design basis earthquake levels. It was also observed that more RC coupling beams required repair following a design basis earthquake than the number of VCDs needing repair. In addition, the modular nature of the VCDs would also facilitate repair of any damaged elements.

The results from this study are based solely on a preliminary VCD design and no optimization of the damper performance was investigated. Further studies will include varying the size and number of the VE material layers, optimizing the number of VCD elements used at each floor level, and varying the fuse activation force in order to arrive at a more effective design strategy.

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