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Optimal placement of coupling elements of RC shear walls using endurance time method

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Abstract

Shear wall is one of the common lateral bracing systems in reinforced concrete structures. A coupling beam can be used due to architectural limitations for connecting two or multiple separate walls. Coupling beams are the most vulnerable elements of coupled shear wall systems. Therefore, beams could be designed to act as replaceable fuses in the system. This paper investigates the application of viscoelastic coupling dampers (VCD) and replaceable steel coupling beams in a high-rise building in a high seismicity region. A parametric study has been performed to determine the most effective number and location of the dampers to acquire enhanced seismic performance of the structure. The endurance time analysis method has been utilized to compare the seismic performance of a conventional steel coupled wall building to alternative designs incorporating VCD. The results show that the structure with positioning the coupling beams of P2 in which 25% of coupling beams are VCD has had 21% less inter-story drift ratios compared to P1, where all coupling beams are replaceable steel coupling beams (RSCBs). VDCs allow the natural period of the structure to enhance. By replacing the RCSB with less stiff VCDs, the lateral stiffness of the structure is reduced and the natural period is shifted beyond the predominant periods of regular earthquakes. The added damping provided by using the VCDs dissipates seismic energy and efficiently controls excessive drifts.

Keywords: Endurance time method; RC shear walls; Coupling beams.

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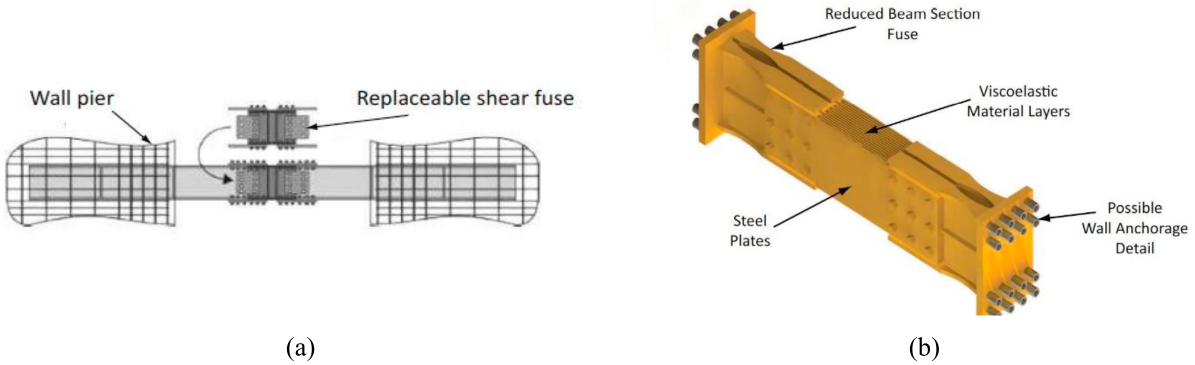
1. Introduction

Reinforced concrete (RC) shear walls are generally used in tall buildings due to their lateral load resisting capacity and stiffness in resisting earthquake-induced forces . Many researches were carried out to investigate the behavior of shear walls with openings as presented by Afefy (2020), AlHamaydeh et al. (2022), Bypour et al. (2021), Ji et al. (2018), Yang et al. (2022), and Moradi et al. (2020). Based on architectural demands, coupling beams are shaped, which provides more opportunities for openings on RC shear walls. Coupling beams in RC shear walls are recommended to yield and dissipate seismic energy before damaging wall piers. However, reports on the past observations of damaged structures have shown that the RC coupling beams have been seriously damaged due to past severe earthquakes, as discussed by Kheyroddin & Emami (2019). Unlike the RC coupling beams, the most important advantages of steel coupling beams are ductile behavior and their excellent ability to dissipate energy. The steel coupling beams in RC shear walls have been studied over the last two decades to illustrate their advantages in terms of constructional efficiency and size reduction compared to RC coupling beams based on Fortney et al. (2007) and Wang et al. (2021).

A replaceable steel coupling beam (RSCB) was developed to enhance the resilience capacity. It comprises a middle fuse shear link connected to regular steel segments at its two ends, which are designed to remain elastic, as investigated by Ji et al. (2017). During a severe earthquake, the fuse shear links yield and dissipate seismic energy, and as soon as they are damaged, they can be replaced due to specialized link-to-beam connection details (see Fig. 1(a)). Viscoelastic coupling dampers (VCD) are made up of several layers of viscoelastic material bonded to layers of steel plate, (see Fig. 1(b)) based on Jiang et al. (2022) and Montgomery et al. (2021). The plates are anchored at alternating ends to built-up steel sections. These dampers can be used to replace RC or steel coupling beams in a coupled wall high-rise building as discussed by Montgomery et al. (2021). The VCDs can be utilized instead of RC coupling beams to take advantage of shear deformations between adjacent RC shear walls during lateral loading of the structure based on Montgomery & Christopoulos (2014). When the structure is subjected to frequent or design-level earthquakes, the damper provides both a displacement-dependent elastic restoring force presenting coupling to the walls and a velocity-dependent viscous force, offering supplemental damping to the building based on Montgomery & Christopoulos (2014). A ductile fuse element can also be combined with a damper in high seismicity regions to increase its performance. The fuse is capacity designed such that if predefined load levels are reached in the damper during severe seismic loading, the connection elements act as a force limiting members and prevent damage in adjoining structural elements, as presented by Shahrooz et al. (2018).



(a) (b)

Fig. 1. (a) RSCB concept for steel coupling beams based on Shahrooz et al. (2018) and (b) Viscous coupling damper adapted from Montgomery & Christopoulos (2014).

When a coupled shear wall is subjected to lateral loads, the overturning moment is resisted by moment reactions spread at the base of the wall piers and coupling behavior induced by the coupling beams, as shown in Fig. 2. The degree of coupling (DoC) is determined as the proportion of overturning moment resisted by coupling response. DoC is defined based on Ji & Molina Hutt (2020):

$$DoC = \frac{TL_w}{TL_w + \sum M1{,}2} * 100 \tag{1}$$

where T defines tensile or compressive force in wall piers induced by shear forces of coupling beams, L_w defines the distance between centroids of the adjoining wall piers and $M_{1,2}$ defines the moment at the base of the wall pier. The value of DoC varies as the coupled wall deforms under lateral loading. Generally, DoC is calculated when all of the systems form a mechanism that all coupling beams yield and the wall piers yield at the base. Therefore, the value of DoC reflects the proportional relation of strengths between the coupling beams and the wall piers based on Ji & Molina Hutt (2020).

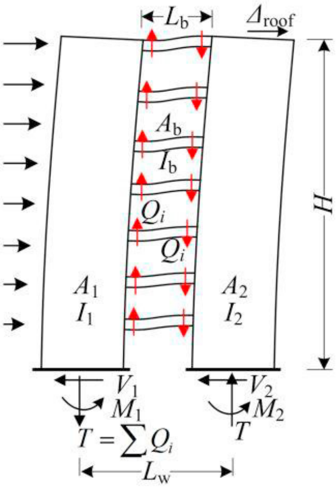


Fig. 2. Lateral load resistance pattern of a coupled wall Ji & Molina Hutt (2020).

Different analysis methodologies have been introduced for seismic performance evaluation of structures, including pushover analysis, incremental dynamic analysis, and endurance time (ET) method as listed by Amirhosein Shabani, Ali Alinejad, et al. (2021) and Amirhosein Shabani, Mahdi Kioumarsi, et al. (2021). The ET method is a time history dynamic analysis in which predetermined intensifying excitations dominate buildings. This method gives a tool for response prediction that complements structural responses to the intensity of earthquakes with a considerably less computational demand than conventional time history analysis, as presented by Estekanchi & Vafai (2021). The increasing trend of ET acceleration function gives a new intention to the time in the ET method, and time in the ET method reflects intensity measures of earthquake motions. At the start of ET excitation, the intensity of motions is low; consequently, ET excitations at initial time intervals are consultants of low-intensity earthquake ground motions. At the mean time interval of ET excitations, the intensity of motions is moderate, and consequently, excitations are envoy of moderate earthquakes. At the end of ET excitations, the intensity is excessive, and ET excitations are consultants of severe earthquakes based on Estekanchi et al. (2020).

In this study, the seismic behavior of a dual system comprising of bending frame and shear wall with various positioning of steel and viscoelastic coupling beams in the height of the shear wall has been investigated. Three levels of seismic hazard, including the operation design earthquake (ODE), the design basis earthquake (DBE), and the maximum considered earthquake (MCE), were considered. It was determined that the VCDs enhance the structural performance of the conventional building in terms of the peak inter-story drift ratios and floor accelerations of the building at all seismic hazard levels. The findings illustrate that utilizing viscoelastic beams in the upper area of the shear turning point of a shear wall does not have any tangible influence on reducing the structure's response compared to steel coupling beams due to the interaction between the wall and frame.

2. Material and Methods

A two-dimensional nonlinear model of an RC structure was constructed using Opensees as established by McKenna et al. (2006). The geometry of the frame and details about modeling the coupling beams are illustrated in Fig. 3(a). The RSCB model includes three key components: shear link, beam segments, and connections among them. The shear link is simulated through a nonlinear zero-length link element. For the shear link which has a length ratio of less than

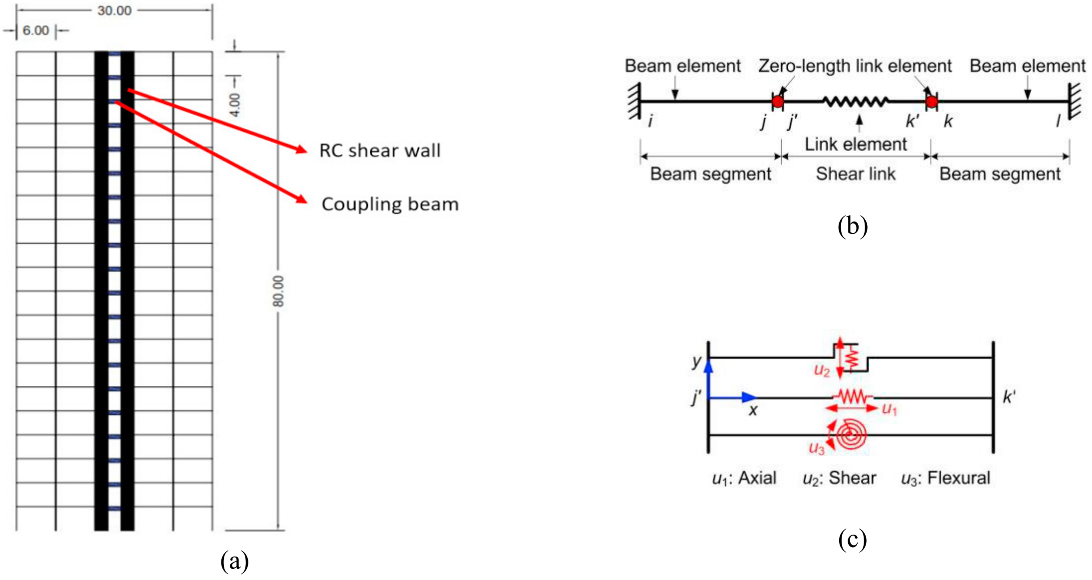
1.6 and is designed to yield in shear, the axial and flexural springs can be elastic, whereas the shear spring is nonlinear. The stiffness of the axial spring (K_a) is calculated as EA/e where E indicates the Young modulus of the steel, A is the cross-sectional area of the shear link, and e indicates the length of the shear link. In addition, the stiffness of the flexural spring (K_f) is calculated as EI/e, where I represents the moment of inertia of steel based on Ji & Molina Hutt (2020). For the shear spring, the yield force V_y and shear stiffness K_s are calculated as follows:

$$V_y = 0.6F_{y,w}A_w \tag{2}$$

$$K_s = \frac{1}{\frac{e^3}{12EI}+\frac{e}{GA_W}} \tag{3}$$

where $f_{y,w}$ indicates the yield strength of web steel, A_w indicates the cross-sectional area of the web, G is the shear module of the web steel, I is the moment of inertia of the section, and e is the length of the shear link based on the deep beam theory presented in A Shabani et al. (2021) Shabani & Kioumarsi (2022).

The properties of the modeled RC sections are shown in Table 1. The properties of the RSCB and VCD have been used based on laboratory research by Mansour et al. (2011) and Montgomery & Christopoulos (2015), respectively. Fig. 4 illustrates the patterns of steel coupling and viscoelastic beams at the height of the shear wall. Nonlinear beam-column elements were used to represent the response of the frame members, and rigid diaphragms were applied to each floor as was done by Zaherdannak et al. (2020). The stress-strain relationships for the confined and unconfined concrete were defined using the Mander model as elaborated by Mander et al. (1988). The material model for reinforcing steel was defined based on the specified yield stress of 400 Mpa. Since structural walls would action complicated nonlinear behavior, a multilayer shell element is recommended for modeling the RC wall piers. Lu et al. (2015) carried out the multilayer shell element in the computation platform Opensees for modeling RC walls. Wu et al. (2018) validated the models by collation with test results and verified that the modeled approach could ensure both computational efficiency and a reasonable level of accuracy. The concrete in structural walls is simulated as the planar concrete constitutive model, based totally on the damage mechanics and the smeared crack model based on Lu et al. (2015). The Menegotto–Pinto material model for steel reinforcement is referred to as Steel02 material in OpenSees developed by McKenna et al. (2006). Gravity loads and seismic masses were computed based on loading information provided in ASCE (2010). The ET method was performed by applying the ETA20jn excitation based on A Mirzaee et al. (2012), which was created for nonlinear analyses based on research by Amin Mirzaee & Estekanchi (2015).



(a)

(b)

(c)

Fig. 3. (a) Scheme of the structure modeled by OpenSees (dimension in meter) , (b) Coupling beam model, and (c) Link element.

Table 1. Properties of the modeled RC sections.

story	Beam			column			Wall		
	b(m)	d(m)	ρ_t(%)	b(m)	d(m)	ρ (%)	l(m)	d(m)	ρ_l(%)
1-5	0.5	0.6	0.5	0.75	0.75	5.5	2.00	0.03	3.0
6-10	0.5	0.6	0.5	0.70	0.70	3	2.00	0.03	2.5
11-15	0.5	0.5	0.4	0.65	0.65	3	2.00	0.03	2.0
16-20	0.5	0.5	0.4	0.60	0.60	3	2.00	0.03	2.0

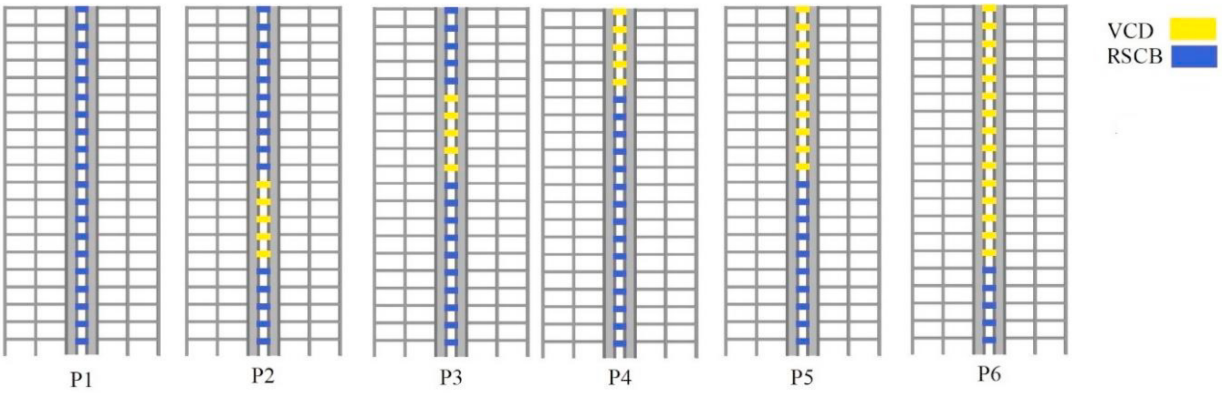


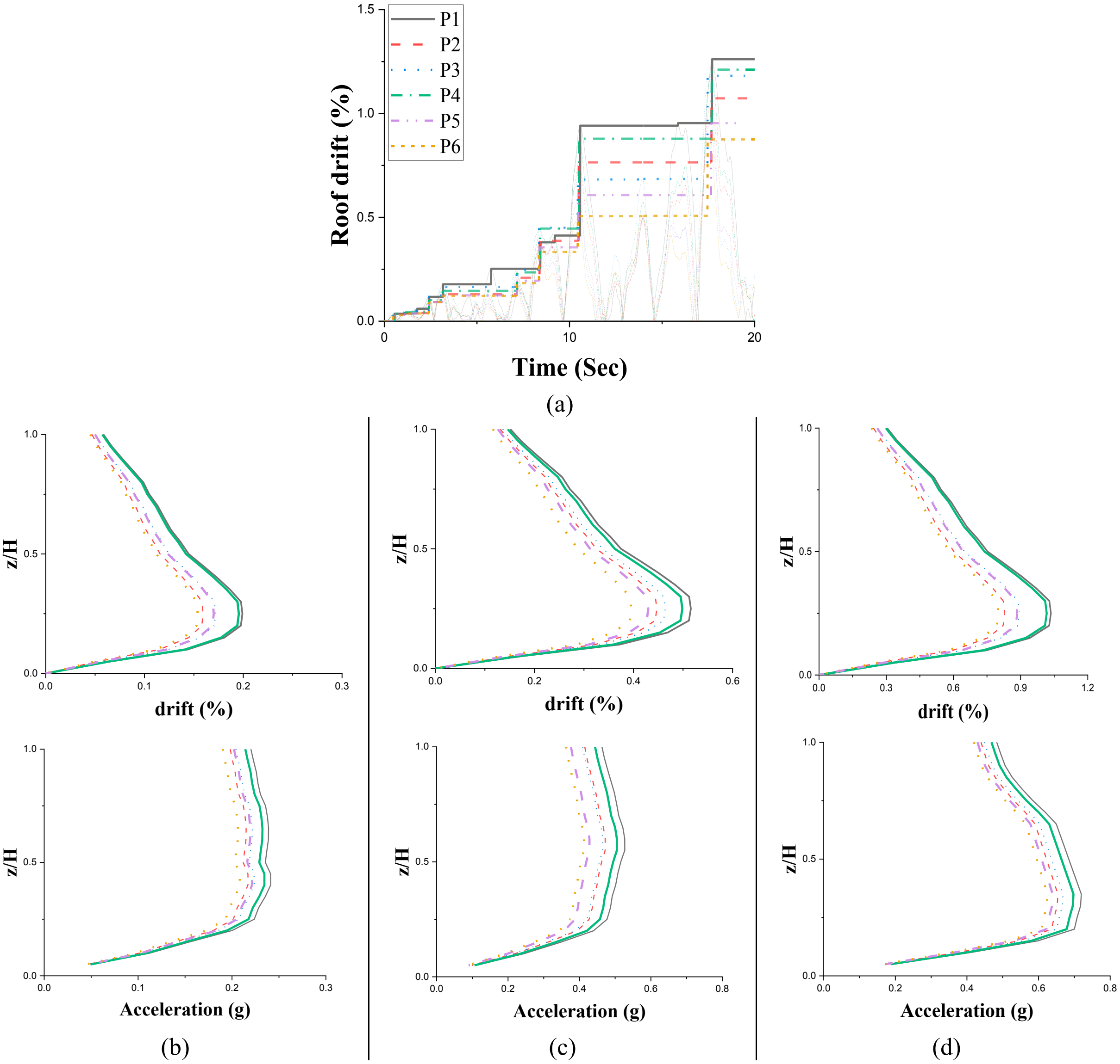
Fig. 4. Patterns of steel coupling and viscoelastic beams in the height of the shear wall.

3. Results and Discussion

Fig.5 (a) shows the ET analysis curves of the roof displacement during the ETA20jn record. It can be concluded that the added damping provided by the VCDs is effective in reducing the resonant response at the top of the structure. Fig.5 (b), (c), and (d) show the peak inter-story drift ratios of the modeled dual system comprising bending frame and shear wall at ODE, DBE, and MCE levels. According to the drift curve of floors, the structure with positioning the coupling beams of P2 in which 25% of coupling beams are VCD has had 21% less inter-story drift ratios than the P1 where all coupling beams are RSCB. The P6 with 75% VCD has had a 5% reduction of inter-story drift ratios compared to the P2 model. Compared to the P1, the maximum values of the peak floor accelerations of the P6 model are reduced by up to 12% under the DBE and 14% under the MCE level ground motions. Based on Fig.5 (b) , incorporating the VCDs in the design leads to significant reductions in floor accelerations throughout the height of the building

Table 2 presents the obtained structural parameters from the ET analysis. Three seismic hazard levels, the ODE, DBE, and the MCE, were considered. The composition VCDs and RSCBs in the height of the shear wall in the P2 and P6 models lead to significant reductions in inter-story drift ratios and floor accelerations of the building. Overall, the maximum values of the peak inter-story drift ratios of the P6 model are reduced by up to 10% under the DBE, and 21% under the MCE level ground motions in comparison with the P1 model. The ductility of the structure rises by increasing the DoC of the shear wall. The structure with RSCB has the lowest period, and increasing the number of VCD leads to the growth of the structural period. It was found that the VCDs improve the structural performance of the conventional building significantly, as indicated by the reductions in the peak inter-story drift ratios, floor accelerations, coupling beam plastic rotations, core wall shear forces, and bending moments of the building at all the seismic hazard levels.

At the DBE and MCE hazard levels, RSCB are expected to undergo inelastic deformations, imparting hysteretic damping to the structure and limiting the transfer of forces to the wall piers. As the coupling beams deform inelastically, the DoC is reduced, and the effective period of the structure is elongated. For seismic applications, a ductile fuse is included in the design of the VCDs. In the event of a large earthquake, the fuse yields or activates, limiting the transfer of forces and protecting the viscoelastic material from excessive shear strains.



(a)

(b)

(c)

(d)

Fig.5. (a) The ET analysis curves, peak Inter-story drift ratio and peak accelerations throughout the building height for (b) ODE and (c) DBE and (d) MCE levels.

Table 2. Structural parameters from the ET analysis.

Pattern	DoC (%)	Period (s)	ODE		DBE		MCE	
			Max Acceleration (g)	Max Inter-story drift (%)	Max Acceleration (g)	Max Inter-story drift (%)	Max Acceleration (g)	Max Inter-story drift (%)
P1	60	2.492	0.221	0.180	0.510	0.52	0.719	1.11
P2	56	2.524	0.212	0.172	0. 439	0.46	0.664	0.88
P3	57	2.517	0.215	0.176	0.450	0.57	0.665	0.93
P4	58	2.511	0.220	0.179	0.504	0.52	0.703	1.14
P5	55	2.535	0.217	0.175	0.428	0.57	0.647	1.00
P6	52	2.551	0.210	0.170	0.410	0.43	0.636	0.85

4. Conclusions

VCD consists of multiple layers of viscoelastic material placed between layers of the steel plate, anchored at alternating ends to built-up structural steel members. The viscoelastic coupling dampers can be used in place of replaceable steel coupling beams to add supplemental distributed damping to a coupled wall building. This paper investigates the application of viscoelastic coupling dampers and replaceable RSCB in a high-rise building in a high seismicity region. A parametric study has been performed to determine the most effective number and location of the dampers to acquire enhanced seismic performance of the structure. In addition, the ET analysis method has been utilized to compare the seismic performance of a conventional steel coupled wall building to alternative designs. The obtained results show that:

- The composition VCDs and RSCBs in the height of the shear wall in the P2 and P6 models leads to significant reductions in inter-story drift ratios and floor accelerations of the building.
- The P2 model, in which 25% of coupling beams are viscoelastic coupling dampers, showed 21% fewer inter-story drift ratios compared to the P1 model, where all coupling beams are replaceable steel coupling beams. The P6 with 75% viscoelastic coupling dampers has had a 5% reduction of inter-story drift ratios compared to the P2 model.
- VCD can be used for elongation of the natural period of the structure. By replacing the replaceable steel coupling beams with less stiff viscoelastic coupling dampers, the lateral stiffness of the structure is reduced, and the natural period is shifted beyond the predominant periods of typical earthquakes.
- VCD improves the structural performance of the conventional building significantly, as indicated by the reductions in the peak inter-story drift ratios and floor accelerations of the building at all seismic hazard levels.
- VCD beams in the upper area of the shear turning point of a shear wall do not have any tangible influence on reducing the structure's response compared to steel coupling beams due to the interaction between the wall and frame.

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