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VISCOELASTIC COUPLING DAMPERS FOR THE ENHANCED SEISMIC RESILIENCE OF A MEGATALL BUILDING

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Abstract

The viscoelastic coupling damper (VCD) has emerged as a promising technology to enhance both the seismic resilience and the wind response of high-rise buildings. In this study the effectiveness of VCDs in enhancing the seismic resilience of supertall and megatall buildings is investigated for a 110-story, 630 m tall building designed using a non-prescriptive performance-based approach. The lateral load resisting system of the building is representative of modern supertall and megatall buildings. Three-dimensional nonlinear models are developed and time-history analyses are carried out under the service level earthquake (SLE), the design earthquake (DE), and the risk-targeted maximum considered earthquake (MCE_R) level ground motions. The VCDs are used in a damped outrigger configuration in combination with VCDs replacing coupling beams in the concrete core to maximize the effect of the added damping on the seismic performance of the structure. It is found that the VCDs result in significant reductions in all response indicators of the building throughout the building height. Over all three seismic hazard levels, VCDs result in 11–25% reductions in median peak inter-story drift ratios and 18–44% reductions in median peak floor accelerations compared with the conventional building. Subsequent financial loss and downtime analyses revealed that the design with the VCDs reduces the direct repair costs in the range of 30–78% over all three seismic hazard levels compared with the conventional building. For the conventional building, the downtimes for functional recovery are estimated to be 1, 5, and 12 months respectively for the SLE, DE and MCE_R level events. These downtimes are reduced by more than 45% after incorporating VCDs. Results of this study indicate that in addition to enhancing resilience of the building by reducing damage and downtime, the VCDs could also provide an opportunity to reduce up-front cost due to reductions in core wall shear forces and bending moments under MCE_R level ground motions.

Keywords: megatall buildings, viscoelastic coupling dampers, seismic resilience, enhanced performance, outriggers

1. Introduction

Recent studies have raised concerns about the seismic resilience of tall buildings and have highlighted the need of high-performance supplemental energy dissipation devices to enhance seismic resilience [1-5]. These studies however, were focused on buildings in the range of about 40 stories. Because of the rapid urbanization and population densification, there is a genuine interest in the construction of supertall (between 300-600 m tall) and megatall (over 600 m tall) buildings in seismically active regions. Such buildings present a unique set of design challenges including their low inherent damping, large gravity loads, P-Delta effects, higher mode effects, and potential damage ranging from minor nonstructural damage to major structural damage distributed throughout the height of the building under a range of seismic hazard levels. For these monumental towers the design life is also much longer than a typical building because of the significance of the structures to their urban setting. The present study is focused on the seismic resilience of much taller modern buildings in the range of 100 stories.

Currently non-prescriptive performance-based methodologies are typically used for the seismic design of supertall and megatall buildings, and resilience is implicitly considered even though damage and repairs are expected under strong earthquakes. Other aspects such as financial losses and downtime are seldom explicitly considered in design. The objective of this study is to assess seismic resilience of a real-world megatall building and investigate benefits of adopting an alternate resilience-based design using viscoelastic coupling dampers (VCDs) for this structure. The VCD is a high-performance damping system that does not occupy any usable architectural space and when properly configured provides supplemental viscous damping and coupling stiffness for dynamic loads ranging from very low-levels of wind-induced vibrations to very large earthquake-induced deformations [6, 7]. High-performance systems also provide opportunities for improving the structural performance while also potentially achieving reductions in materials and construction cost of the main structure.

In an earlier study [5], a new strategy to enhance seismic resilience of tall buildings was introduced wherein an optimum combination of VCDs in outriggers and core coupling beams was found to offer significant benefits in enhancing seismic resilience of a shorter (40-story) reinforced concrete (RC) core-wall building. The present paper uses the same strategy to investigate seismic resilience of a megatall building subject to service level earthquake (SLE), design earthquake (DE), and risk-targeted maximum considered earthquake (MCE_R) level ground motions through three-dimensional nonlinear models and response time-history analyses. The lateral load resisting system of the building is representative of modern supertall and megatall buildings. The results for each earthquake hazard level are presented in terms of various peak response indicators, non-structural and structural repair costs, and expected downtime. This study provides insights into the performance of current high-rise buildings located in seismically active regions around the world and offers guidance on a potential alternate design approach using high-performance VCDs.

2. Building Description

2.1 Conventional Building and Design Philosophy

The building considered in this study is a 110-story, 630 m megatall building with a total gross floor area of more than 330,000 m^2 designed for a highly seismic region (Fig. 1(a)). The building also incorporates an additional 6 stories below grade and a 3-story observation deck at the top. Note that the location of the building is not presented here for confidentiality reasons. The design of the building was governed primarily by the seismic loading. The primary lateral load resisting system consists of a reinforced concrete (RC) coupled core wall and a steel truss outrigger system that connects the core with the super columns. The secondary lateral load resisting system consists of a mega frame comprised of the super columns and belt trusses together with the steel outrigger system. The building was designed in accordance with the 2012 International Building code using a non-prescriptive performance-based approach. The performance objective under the MCE_R level ground motions was to achieve life-safety. Moderate nonlinearity was allowed under the DE level ground motions while the structure was expected to remain essentially elastic under the SLE ground motions. The design response spectra corresponding to these various hazard levels are plotted in Fig. 2(a). As per the current state-of-the-practice, for the SLE and DE, response spectrum analyses were carried out in ETABS [8] while for the MCE_R, nonlinear response history analyses (RHAs) were carried out in Perform-3D [9] using a set of 7 ground motions spectrally matched to the design response spectrum per ASCE 7-10 [10] as shown in Fig. 2(b). The nonlinear model in Perform-3D [9] was consistent with the current state-of-the-practice in nonlinear modeling of tall buildings [5]. The acceptance criteria were mainly based on the PEER TBI guidelines [11] and the LATBSDC [12] guidelines.

2.2 Alternate Design using Viscoelastic Coupling Dampers (VCDs)

An alternate design wherein the VCDs are placed in multiple outriggers in combination with the VCDs replacing about 60% of the diagonally reinforced concrete coupling beams in the core throughout the height of the building was developed (Fig. 1(b)). Four VCDs were placed at each outrigger location while one VCD was used at each coupling beam location in the core. The steel outriggers were replaced with a reinforced concrete (RC) wall with openings for ease of construction and in order to increase the effectiveness of the dampers. This particular configuration was chosen because previous studies have shown that it is effective in reducing all response indicators of the building [5]. Each VCD was modeled in Perform-3D [9] using a spring element to simulate the connection stiffness in series with a generalized Maxwell model (GMM) which consists of one spring element in parallel with two Maxwell elements. This model is capable of simulating frequency dependency of the viscoelastic (VE) material and has been extensively validated using full-scale test results of the VCDs as shown in Fig. 3. Further details on numerical modeling of the VCDs can be found elsewhere [13]. For the building considered in this study, a reference temperature of 24^0 C was used to calculate the VCD parameters because the VE material properties of the VCDs are not expected to change significantly during seismic loadings [13] for buildings with such long fundamental periods for typical damper designs. Since outrigger VCDs can be subjected to extreme strain demands on the VE material under MCE_R level events, a lockup mechanism was designed for the outrigger VCDs to lockup at 300% strain. In this design, the connecting element of the VCD was capacity-designed to yield when the shear strain in the VE material reaches 300%. The lockup mechanism prevents any deformation in the VE layer beyond this strain limit and forces the connecting elements to yield. Since outrigger VCDs are only located at few locations along the height of the building, the steel connecting fuse elements can be inspected after a major seismic event and repaired or replaced if required. A typical outrigger VCD with a lockup mechanism is shown in Fig. 1(c) and a typical hysteresis loop of the VCD is shown in Fig. 1(d).

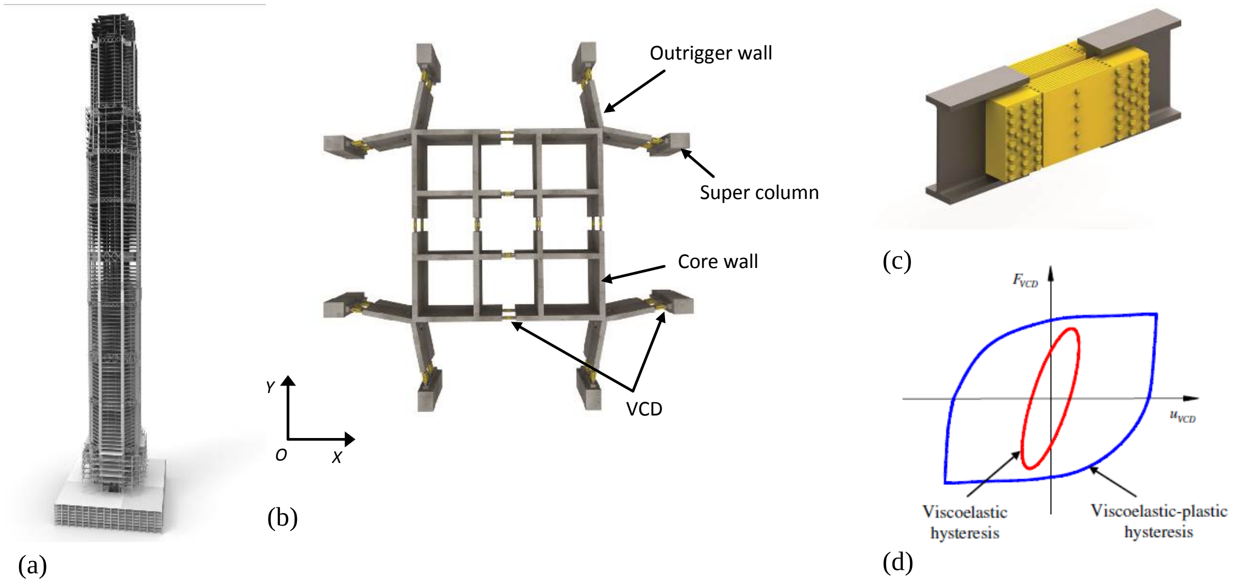

Fig. 1. (a) Isometric view of the megatall building considered in this study; (b) a typical core-wall outrigger system with VCDs (belt trusses are not shown for clarity); (c) a typical outrigger VCD; (d) viscoelastic hysteretic envelopes for wind and moderate earthquake loading and viscoelastic-plastic hysteretic envelopes for extreme seismic loading.

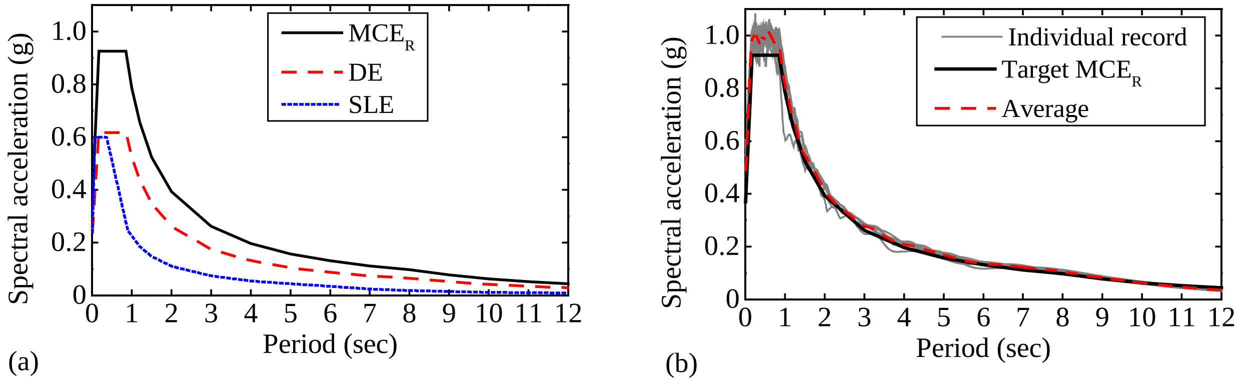

Fig. 2. (a) Design response spectra for different seismic hazard levels and (b) comparison of individual scaled ground motion maximum direction response spectra as well as their average with the risk-targeted maximum considered earthquake (MCE_R) spectrum.

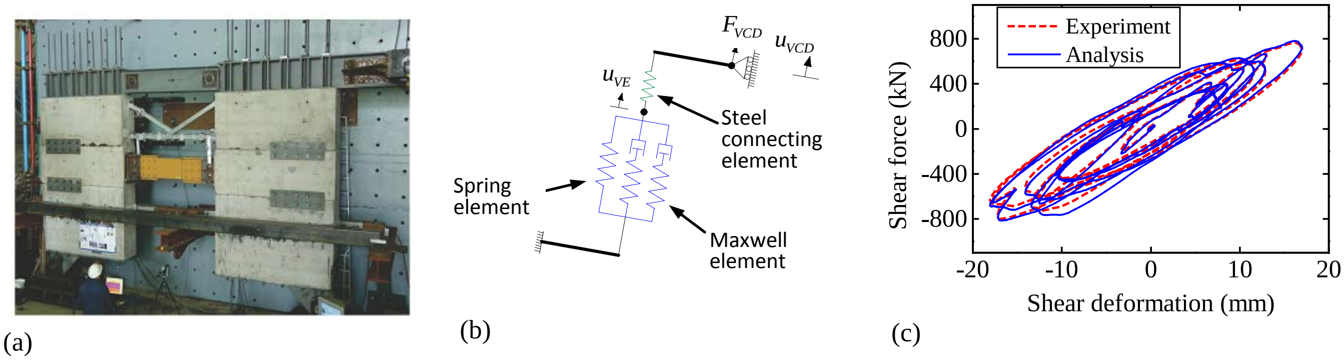

Fig. 3. (a) Full-scale experimental setup of a VCD (adapted from [6]); (b) schematic of the numerical model of the VCD; and (c) a typical comparison of experimental and numerical analysis results from earthquake simulation.

3. Analysis Results and Discussion

3.1 Structural Response Indicators

The building response in the X- and Y-directions is discussed in terms of the peak values of inter-story drift ratio, absolute floor acceleration, coupling beam plastic rotation, core wall shear force ratio (shear force divided by the total seismic weight of the building), and core wall bending moment ratio (bending moment divided by the total seismic weight of the building multiplied by the total height of the building), evaluated as median responses obtained from the time-history analyses using all 7 ground motions. Force-deformation hysteresis loops are also presented for selected cases. The coupling beam plastic rotations were taken as the maximum plastic rotation of all beams at each floor in each direction, with zero plastic rotation implying an elastic response. The building without the VCDs is referred to as the *conventional building* while the one with the VCDs is referred to as the *damped building*.

Changes in the maximum values of peak response indicators of the damped building along X- and Y-directions are compared to those of the conventional building in Table 1. Since in general, the Y-direction peak response indicators were found to be larger than those in the X-direction, Y-direction peak inter-story drift ratio and peak floor acceleration profiles are plotted in Fig. 4 for the SLE, DE, and MCE_R level ground motions. It can be observed from these plots that the response indicators of the conventional building are within design limits with the peak inter-story drift ratio under the MCE_R level ground motions being less than 0.7%. This is because of the presence of several outriggers along the height of the building, which help limit the peak inter-story drifts sustained by the structure. Also, the peak floor accelerations in the conventional building remain below 0.5g over the height of the structure. As can be seen in Fig. 4, the incorporation of the VCDs in the design leads to significant reductions in inter-story drift ratios and floor accelerations throughout the height of the building. Overall, the maximum values of the peak inter-story drift ratios are reduced by up to 25% under the SLE, 23% under the DE, and 15% under the MCE_R level ground motions when compared with the conventional building (Table 1). Similarly, peak floor accelerations are reduced by up to 44% under the SLE, 31% under the DE, and 24% under the MCE_R level ground motions compared with the conventional building (Table 1). Under the MCE_R level ground motions where the coupling beam plastic rotations, and the core wall shear forces and bending moments, which are of critical importance for the overall safety of the system, are plotted for the Y-direction of the building in Fig. 5. In the conventional building, many RC coupling beams suffer plastic rotations in excess of 1% to 2% (Fig. 5(a)), which correspond to minor damage and moderate damage, respectively [14]. It was found that on average about 500 coupling beams in the conventional building suffer minor damage, while about 100 coupling beams suffer moderate damage. Because of the addition of the VCDs and also because of the elimination of most of these coupling beams, plastic rotations are limited to within 1% with most of the plastic deformations being concentrated at upper stories (Fig. 5(a)), indicating that the coupling beams require essentially no repair. Since the seismic design of the core walls in tall buildings is usually governed by shear forces under the MCE_R level ground motions, significant reductions in shear forces throughout the height of the building (although base shear force is not significantly changed in the damped building) indicates that the thickness of the core wall can be reduced in the damped building leading to an up-front cost reduction (Fig. 5(b)). Moreover, since the MCE_R level bending moments are used to design foundation of the building, a significant reduction (28% reduction in the X-direction; Table 1) in the base bending moment could result in a reduction in the cost of the foundation as well (Fig. 5(c)).

In order to examine how the lockup mechanism for the VCDs works under the MCE_R-level ground motions, shear force-deformation relationships for different components of a set of 4 VCDs at an outrigger location are plotted for a particular earthquake ground motion in Fig. 6. Each of the 4 connecting elements which act as a fuse had a capacity of 5,000 kN each leading to a total capacity of 20,000 kN per set of VCDs. As can be seen in Fig. 6(a), because of the lockup mechanism, VE deformation is limited to about 40 mm, which corresponds to 300% shear strain of the VE material. Note that in this case the fuse first yields slightly before the 300% shear strain limit is reached in the VE material (Figs. 6(a) and (b)). The overall combined viscoelastic-plastic force-deformation relationship of the VCD is shown in Fig. 6(c).

Table 1 – Changes in maximum values of peak response indicators of the damped building in comparison with the conventional building, evaluated using the median response.

	Inter-story drift ratio		**Floor acceleration**		**Coupling beam plastic rot.**		**Core wall shear force**		**Core wall bending moment**	
	***X*-dir.**	***Y*-dir.**	***X*-dir.**	***Y*-dir.**	***X*-dir.**	***Y*-dir.**	***X*-dir.**	***Y*-dir.**	***X*-dir.**	***Y*-dir.**
SLE	-25%	-21%	-44%	-41%	-100%	-100%	-28%	-38%	-35%	-52%
DE	-17%	-23%	-29%	-31%	-84%	-68%	-8%	-17%	-39%	-35%
MCE_R	-11%	-15%	-18%	-24%	-77%	-63%	–	-12%	-28%	-26%

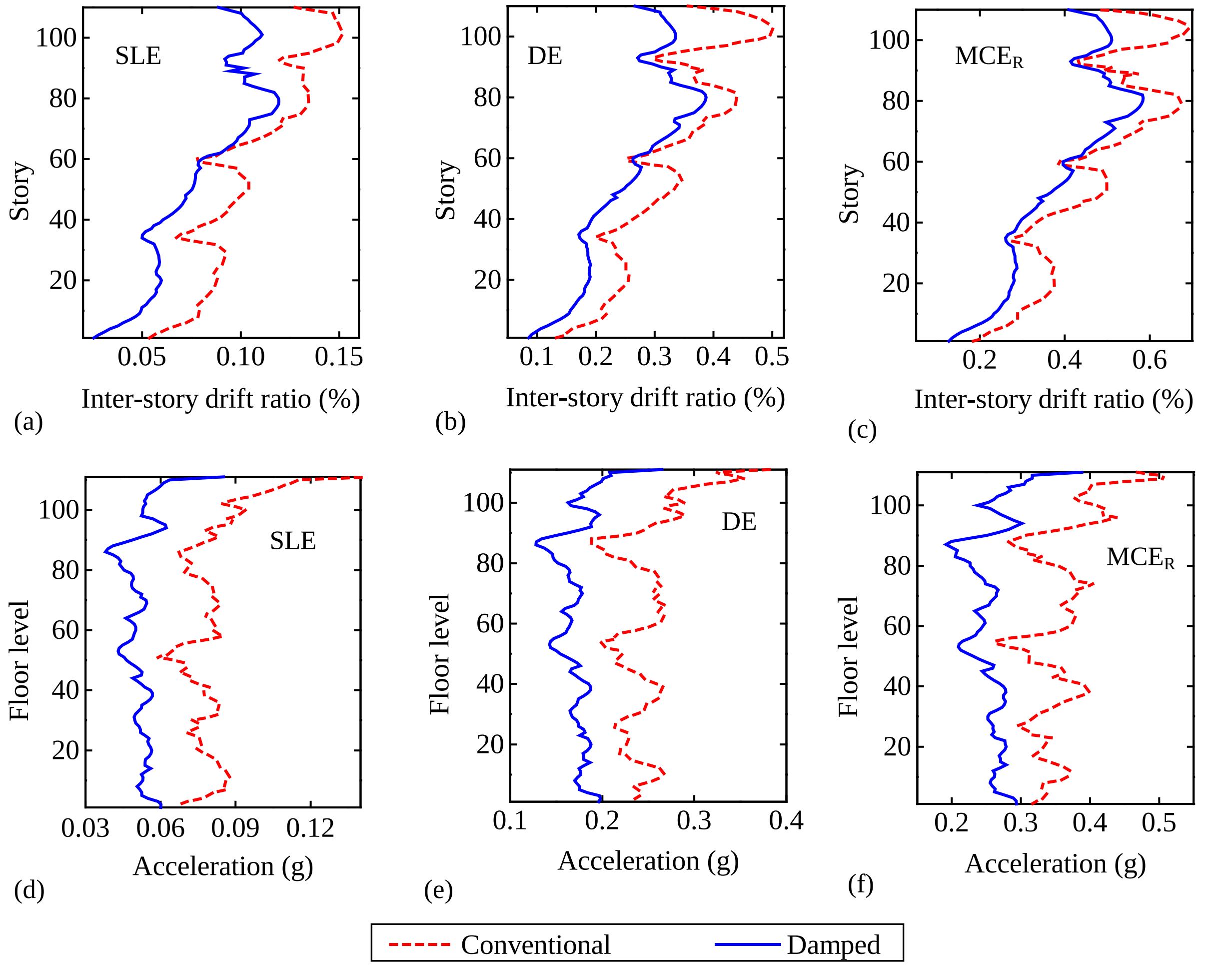

Fig. 4. Median values of Y-direction peak response indicators for various seismic hazard levels: (a)–(c) inter-story drift ratio and (d)–(f) absolute floor acceleration.

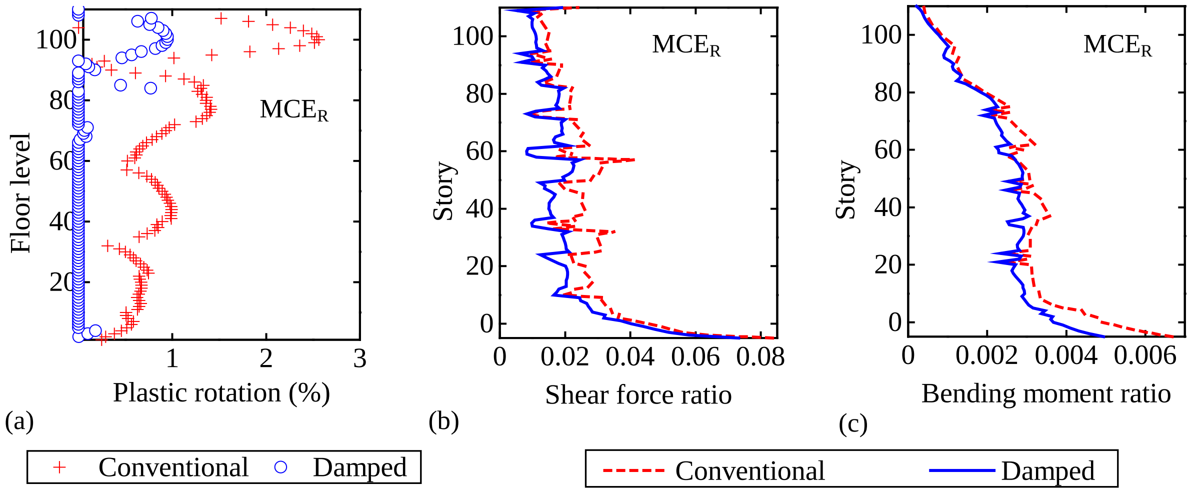

Fig. 5. Median values of Y-direction peak response indicators for MCE$_R$ level ground motions: (a) coupling beam plastic rotation; (b) core wall shear force ratio; and (c) core wall bending moment ratio.

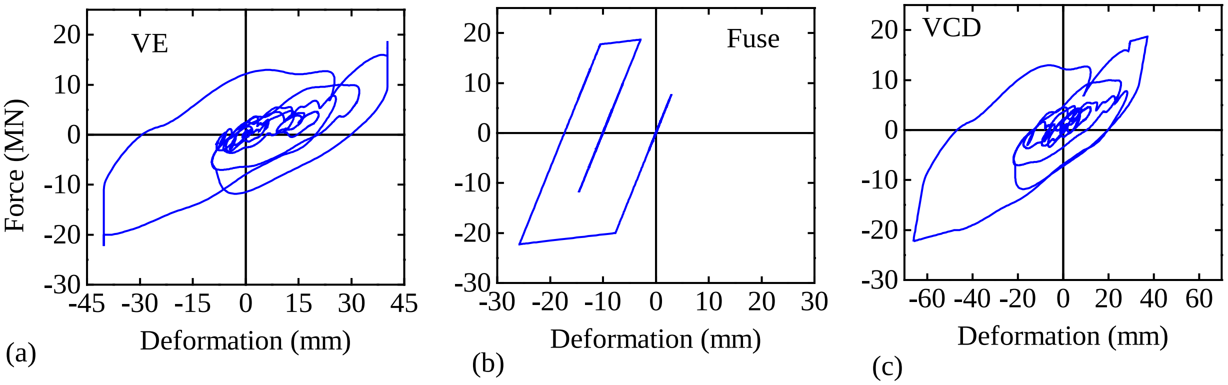

Fig. 6. Shear force deformation relationships for 4-VCDs at an outrigger location under MCE_R-level EQ #5 for: (a) viscoelastic (VE) material; (b) connecting elements i.e., fuse; and (c) entire VCDs (the VE material in series with the fuse). A set of 4 VCDs was used at each outrigger location in the building.

3.2 Financial Losses and Downtime

The SP3 program [15] was used to conduct intensity-based financial loss and downtime estimations of the conventional as well as the damped buildings under the three seismic hazard levels considered in this study. SP3 uses the loss estimation methodology of the ATC-58 project [16] which is also available in PACT [17] and the REDi [18] downtime estimation methodology. To assess structural losses, slab-to-column and equivalent slab-to-wall connections, and coupling beams were included in the performance assessment model. For the non-structural element loss assessment partitions, curtain walls, stairs, suspended ceilings, independent pendant lighting fixtures, cold water piping, HVAC systems, and fire sprinklers were included. The Normative Quantity Estimation tool developed as part of the ATC-58 project was used to obtain typical quantities of non-structural elements based on the gross floor area. Individual tenant's contents were not included in the model. Peak values of inter-story drift ratios, coupling beam rotations, and floor accelerations from all 7 ground motions were input in SP3 and 2,000 Monte-Carlo simulations (minimum number of simulations allowed in SP3) were performed. Because of the current limitations in the number of stories that can be used in the program, only the first 100 floors of the buildings were included in the loss and downtime assessment model and the results were uniformly scaled up by 10% to take into account the additional floors of the building. SP3 reports direct repair costs for each component and downtime evaluated as the arithmetic average of all 2,000 simulations, which are plotted in Figs. 7 and 8 for all three seismic hazard levels. As observed from Fig. 7, VCDs result in significant reductions in repair costs for different components of the building. In the damped building, the total repair costs are reduced by 78% under the SLE, 35% under the DE, and 30% under the MCE_R level events compared with the conventional building. Clear and substantial benefits of the VCDs are evident at lower but more frequent seismic events. For this megatall building, direct repair costs are however only a small fraction of the financial loss that will be incurred due to downtime (Fig. 8). It is clear from Fig. 8 that the damped building suffers smaller downtimes for all levels of recoveries (i.e., re-occupancy, functional recovery, and full recovery) compared with the conventional building. In particular, for the functional recovery, the conventional building needs to be closed for 1 month after the SLE, for 5 months after the DE, and for 12 months after the MCE_R level events. In the damped building, the time required for the functional recovery is reduced by 100% for the SLE, 62% for the DE, and 46% for the MCE_R level events compared with the conventional building. More interesting are the results for the SLE events which show that the conventional building which requires downtime of about 1 month for functional recovery, can maintain its functionality immediately following an SLE level event if the VCDs are used. Assuming that the owner is renting the property at \$2.8 per sq. ft. per month, which is typical in the location of the building, the cost for 1 month of downtime for the entire building adds up to \$12M.

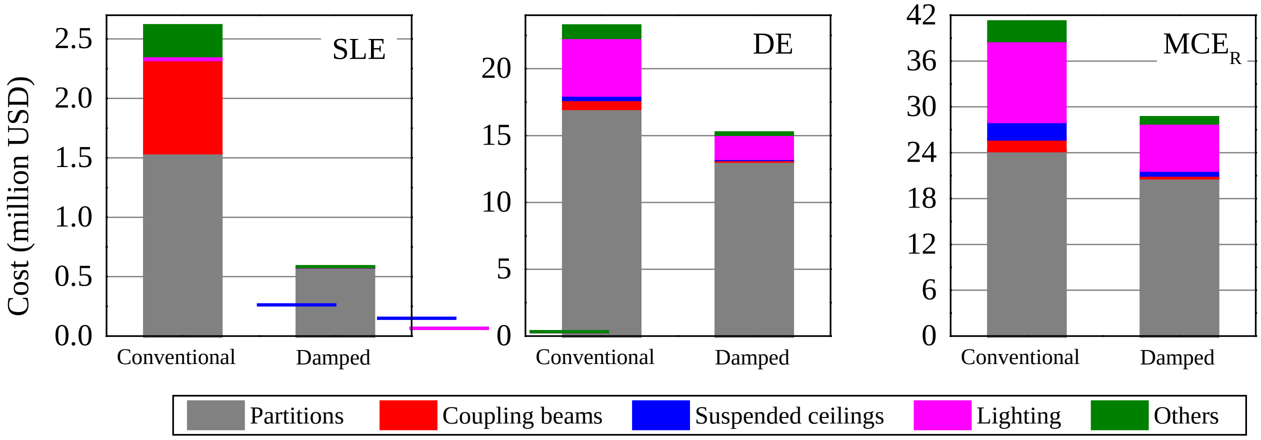

Fig. 7. Direct repair costs of the conventional and the damped buildings for different seismic hazard levels.

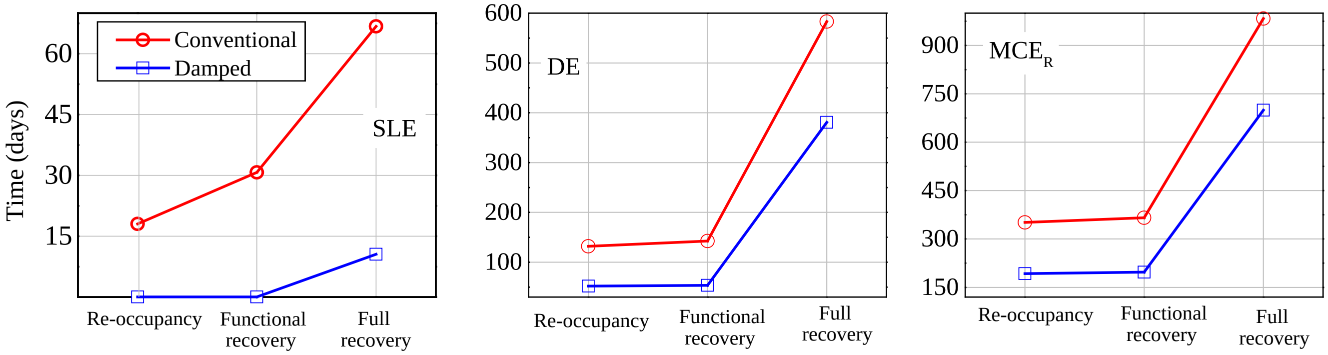

Fig. 8. Recovery times evaluated using REDi methodology [18] for the conventional and the damped buildings for different seismic hazard levels.

4. Concluding Remarks

The seismic resilience of a 110-story megatall building with and without viscoelastic coupling dampers (VCDs) was investigated through three-dimensional nonlinear analyses and state-of-the-art financial loss and downtime assessment methodologies. The VCDs were used in a damped outrigger configuration in combination with VCDs replacing coupling beams in the concrete core. Three levels of seismic hazard, the service level earthquake (SLE), the design earthquake (DE), and the risk-targeted maximum considered earthquake (MCE_R) were considered. 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, and core wall shear forces and bending moments of the building at all the seismic hazard levels. In terms of the peak response indicators, the conventional building was found to behave as expected in the performance-based design but financial losses and downtime particularly for the SLE events were very large. It was revealed that the VCDs provide significant reductions in financial losses and downtime at all the seismic hazard levels but the advantages of the VCD damped structure were more evident at service level earthquakes, wherein immediate functional recovery was possible because of the incorporation of the VCDs. Overall findings of the study suggest that the proposed approach of using VCDs in outriggers and core beam locations that had previously been found to significantly improve the resilience of shorter high rise buildings, also represents a very effective design approach alternative to conventional coupling beam and outrigger structural systems for supertall and megatall buildings.

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