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Applications of Solid Viscoelastic Coupling Dampers (VCDs) in Wind and Earthquake Sensitive Tall Buildings

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Abstract

Solid Viscoelastic Coupling Dampers (VCDs) provide distributed damping that improves the dynamic performance of tall buildings for both wind-storms and earthquakes for all amplitudes of vibration. They are configured in place of typical structural members in tall buildings and therefore do not occupy any architectural space. This paper summarizes the research and development at the University of Toronto in collaboration with Nippon Steel Engineering, 3M and Kinetica over the past two decades. In addition, impact studies on buildings incorporating the VCDs are presented, consisting of a wind sensitive 66-story building in Toronto, a dual-wind and seismic performance-based design of a 4-tower development in Manila and finally a 630 meter Megatall building in Southeast Asia in a severe seismic environment. In all applications the VCDs are shown to provide significant benefits in the dynamic performance under both wind and earthquake loading in a cost-effective manner.

Keywords: Viscoelastic, Dampers, Seismic, Wind, Performance-based

1. Introduction

1.1. Introduction to Solid Viscoelastic Dampers

3M Viscoelastic (VE) dampers were the first damping system to be used in civil engineering structures in 1969, when over 10,000 small VE damper panels were used in each of the World Trade Centers in New York City to improve human comfort in frequent wind vibrations (Mahmoodi et al., 1987). 3M VE dampers were subsequently used in the Columbia SeaFirst building and Two Union Square building in Seattle for wind vibration mitigation, both built in the 1980s (Skilling et al. 1986 and Keel and Mahmoodi, 1986). Subsequently VE dampers were used in a number seismic applications including the seismic retrofit of the Santa Clara County Building (Crosby et al., 1994) and the seismic retrofit of the Los Angeles Police Department New Recruit Training Center (Kanitkar, et al. 1998), amongst others.

Since then, there have been over 300 projects using 3M VE dampers in some of the most demanding wind and earthquake environments throughout the world in different configurations. Since these early applications, the 3M Viscoelastic material has evolved greatly into what is currently a "fourth generation material", the ISD111H. This glassy copolymer, which was developed specifically for tall and supertall buildings, has increased stiffness and damping and enhanced durability. Viscoelastic materials transform vibrational input energy into heat, and at typical building and loading conditions their mechanical properties depend mainly on frequency. Viscoelastic ISD111H material has been thoroughly tested and infor-mation can be found in Montgomery and Christopoulos, 2014 and Pant et al., 2019.

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1.2. Viscoelastic Coupling Dampers

VE dampers are typically configured in brace or wall panel configurations to capture racking (or shear type) deformations in low to mid-rise frame buildings. The most common tall building configurations today however are built using Reinforced Concrete (RC) Coupled Walls, RC core walls and outrigger type configurations. Dampers that are activated by inter-story shear deformations, such as braces or wall panel configurations are not as efficient for these tall RC buildings, which undergo dominant cantilever flexural deformations under lateral loads. In these types of RC buildings, the primary lateral load resisting systems are formed by vertically extending structural elements that are coupled to one another using coupling beams or outriggers. Viscoelastic Coupling Dampers (VCDs) are introduced in lieu of a number of these RC coupling members such that they efficiently add damping to the building structure under wind and earthquake vibrations while still providing a coupling restoring force.

The VCDs utilize multiple layers of solid viscoelastic (VE) material sandwiched between, and bonded to, multiple steel plates, with each layer extending out and anchored into the vertically extending structural members (see Figure 1).

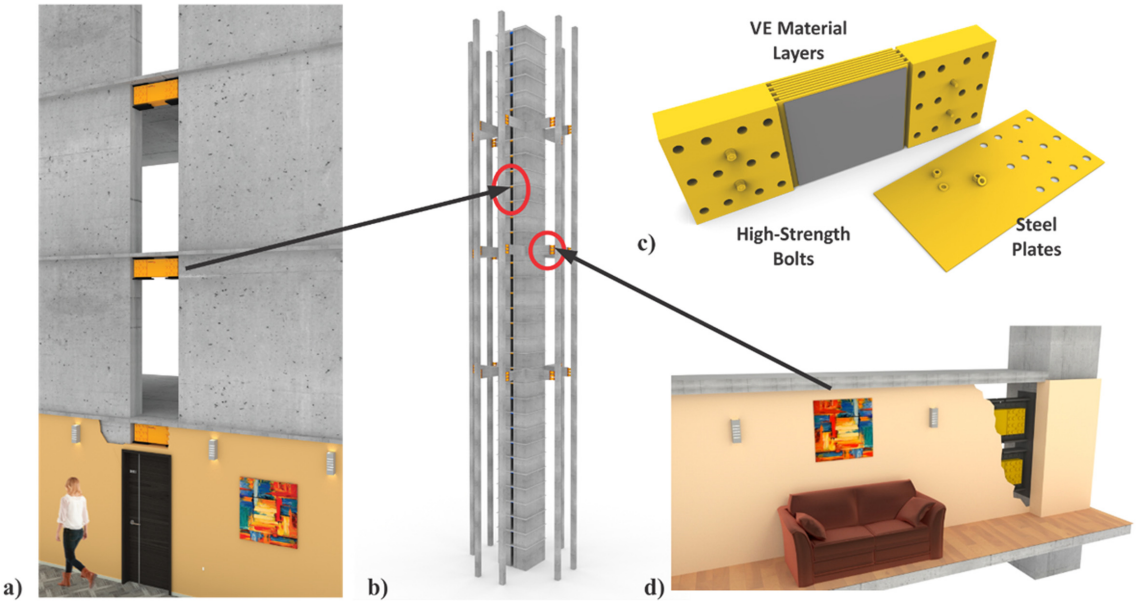


Figure 1. Viscoelastic Coupling Dampers (VCDs) a) reinforced concrete (RC) core configuration, b) tall RC building lateral load-resisting system, c) Viscoelastic damper panel and d) outrigger configuration.

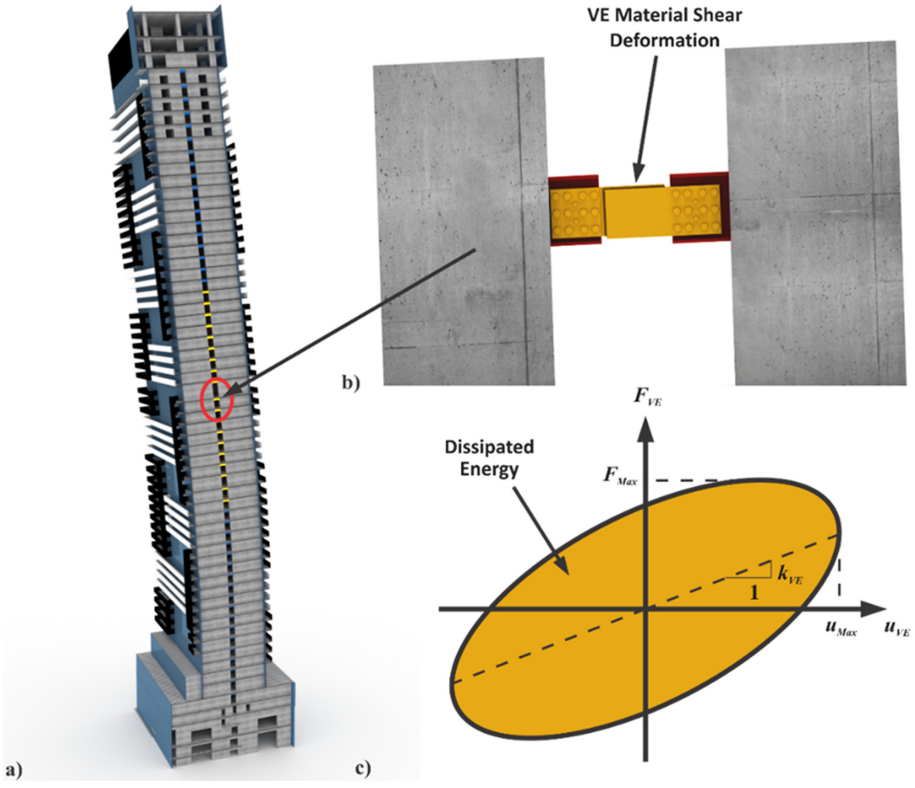


Figure 2. VCD kinematics and mechanical response a) kinematics of tall reinforced concrete (RC) coupled wall building with VCDs, b) kinematics of VCD and c) hysteretic response of VE material.

When the building is subjected to wind storms or earthquakes that cause lateral vibrations, the reinforced concrete walls rotate and undergo axial deformations causing the solid Viscoelastic material to deform in shear (Figure 2a and 2b). These shear deformations acting on the solid Viscoelastic material result in an instantaneous velocity-dependent force, providing viscous damping to the building as well as an instantaneous displacement-dependent elastic restoring force coupling the inter-connected elements during the dynamic response (Figure

2c). For frequent low amplitude wind vibrations through hurricane level wind storms and for frequent earthquakes through maximum credible level earthquakes, the VCDs provide distributed viscous damping for all types of lateral loads (Christopoulos and Montgomery, 2013).

1.2.1. Full-scale Tests

The VCD has been tested in small-scale and full-scale both uniaxially and with two different shear racking configurations to confirm the system performance (Montgomery and Christopoulos, 2014, Pant et al., 2019 and Ardila et al., 2019). Figure 3 shows a full-scale VCD test carried out at the University of Toronto in a uniaxial configuration at a frequency of 0.15 Hz. This VCD specimen consisted of 17 solid VE layers of 330 × 520 mm with 6.5 mm-thickness of high damping ISD111H material bonded to steel plates. Viscoelastic dynamic properties such as shear storage and loss moduli for the ISD111H material can be found in Montgomery and Christopoulos, 2014 and Pant et al., 2019. As can be seen in the test results the backbone viscoelastic hystereses are essentially the same from 0.003 mm up to 9 mm displacements through the damper. This demonstrates a unique characteristic of this solid viscoelastic material whereby it provides a robust viscoelastic response for extremely low amplitude service level wind loading and frequent earthquake vibrations through larger amplitude design level wind and earthquake loads.

A Kelvin-Voigt solid model, which consists of a spring and dashpot in parallel, can be used to describe the dynamic VE material behavior at a given frequency of vibration. The force of the VE material, $F_{VE}(t)$, at a time, t, is expressed as:

$$F_{VE}(t) = k_{VE}u_{VE}(t) + c_{VE}v_{VE}(t) \quad (1)$$

where $u_{VE}(t)$ and $v_{VE}(t)$ are the VE shear deformation and the VE shear deformation rate, respectively at time, t. k_{VE} and c_{VE} are the stiffness and damping coefficients, respectively at a given temperature and frequency. The stiffness and damping coefficients scale up proportional to the bounded area divided by the height of the VE material layers. By carefully selecting the number of layers, the bonding area, and the thickness of the VE material, the VE damper properties can be engineered for a given project specification. By encompassing a large number of layers in parallel, the stiffness and damping properties become very large, approaching the stiffness properties of RC or steel coupling beams which renders them effective for damping tall buildings.

Figure 4a) shows a picture of a full-scale VCD test whereby 2-1,000 kN actuators arranged horizontally push the precast concrete panels causing deformations in VCDs in a shear configuration. Figure 4b) is a photo of the VCD undergoing shear deformation in the racking configuration.

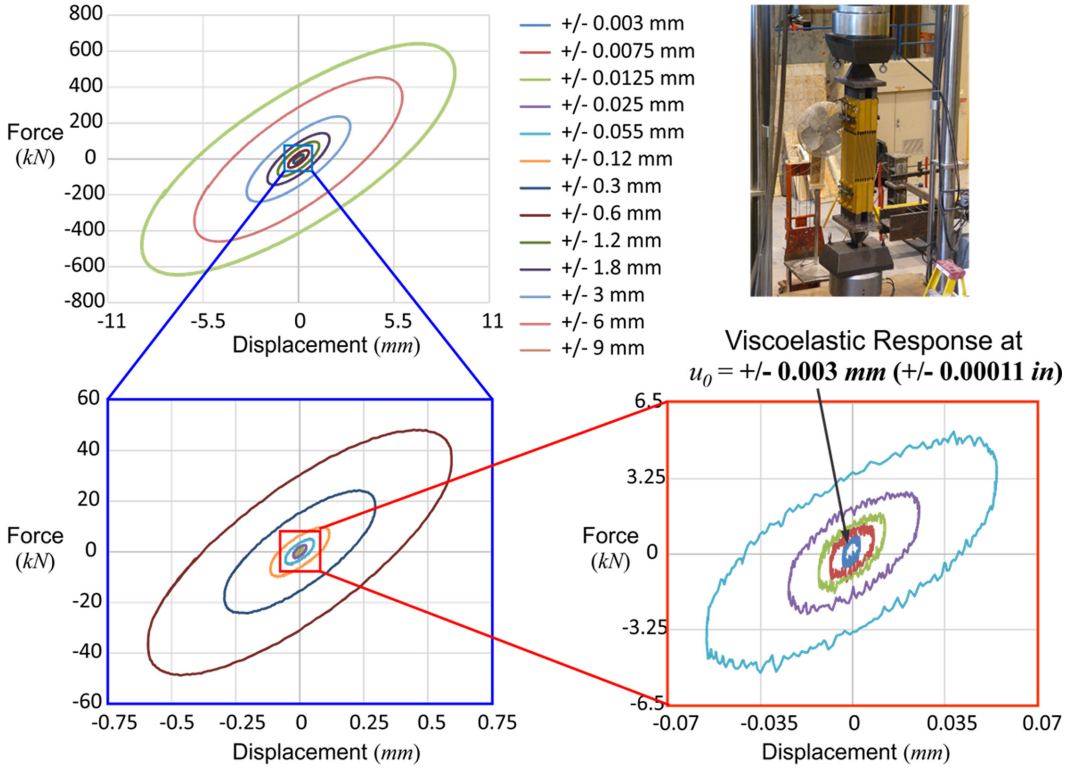


Figure 3. Full-Scale VCDs tested uniaxially at a frequency of 0.15 Hz for strain amplitudes of +/– 0.0003 mm through 10 mm (Photograph by Michael Montgomery)

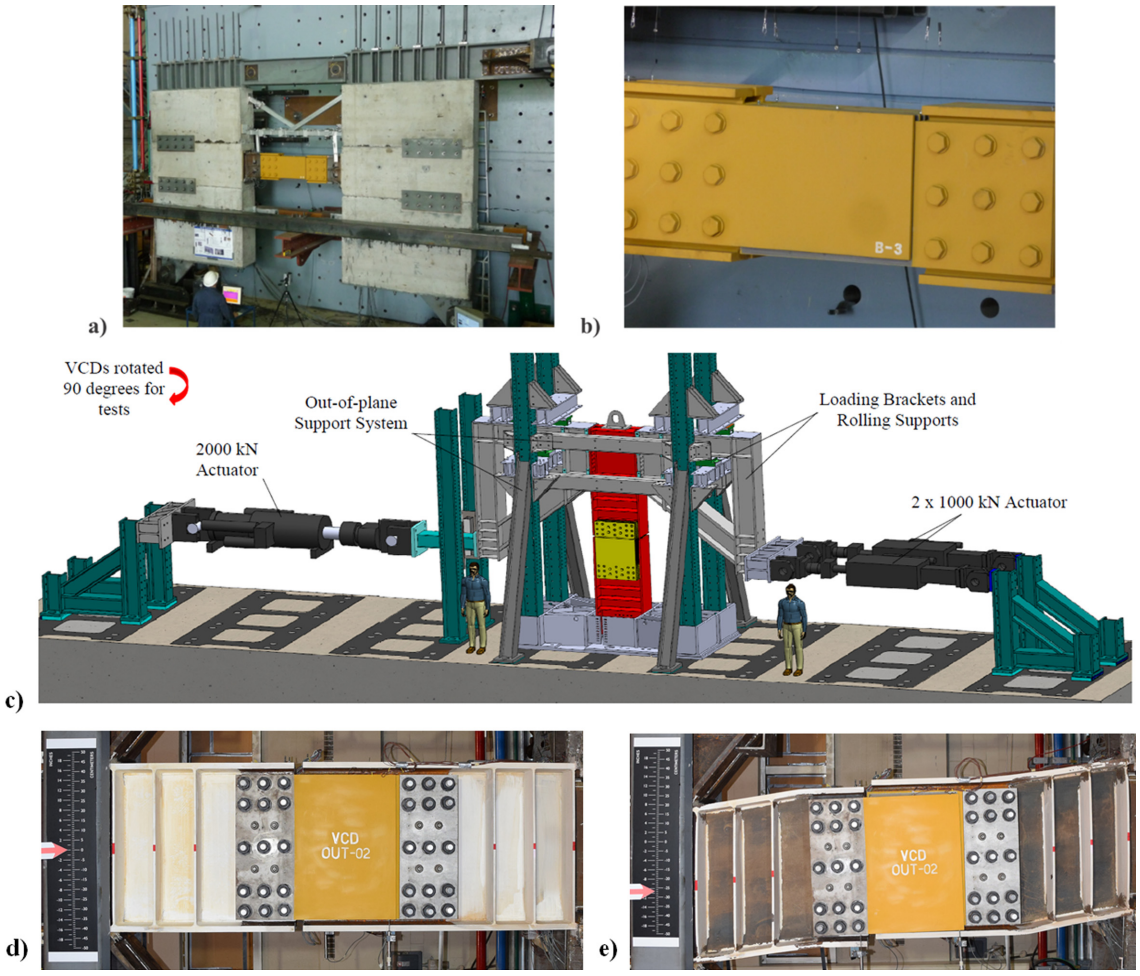


Figure 4. Full-Scale VCDs tested in shear: a) full-scale test setup 1, b) shear deformation in VE material, c) full-scale test setup 2, d) undeformed shape of VCD in setup 2 and e) deformed shape of VCD in setup 2 (Photographs by M. Montgomery and L. Ardila).

Figure 4c) shows a full-scale test setup of the dampers designed for the 630-meter Megatall building described in Section 2.3. This is one of the largest damper tests ever conducted to date worldwide. In this case because of laboratory constraints, the Viscoelastic Coupling Dampers are rotated 90 degrees and configured vertically as opposed to horizontally. The shear deformations are applied to the dampers by 3 actuators capable of achieving a maximum load of 4,000 kN dynamically and a maximum peak velocity of 1000 mm/s. The VCDs were tested with harmonic loads to characterize the damper properties, with simulated wind storms and earthquakes of varying amplitudes. Finally, the steel connecting elements were tested to failure statically and dynamically to study their ductility properties. Figures 4d) and 4e) display the undeformed shape of the VCD and the deformed shape at ultimate deformation of the steel connecting elements, respectively.

Some sample full-scale test results of the test setup 2 are shown in Figures 5a) and 5b). Figure 5a) shows the force vs. displacement results of a VCD tested under harmonic loads at a frequency of 0.1 Hz. As can be seen in Figure 5a), the Viscoelastic response of the VCD in shear is clear and can be represented by Equation (1) modified to include the connection stiffness (Kasai et al. 2006). The force of the VCD, $F_{VCD}(t)$, at a time, t, is expressed as:

$$F_{VCD}(t) = k_{VCD}u_{VCD}(t) + c_{VCD}v_{VCD}(t) \quad (2)$$

where $u_{VCD}(t)$ and $v_{VCD}(t)$ are the VCD shear deformation and the VCD shear deformation rate, respectively at time, t. k_{VCD} and c_{VCD} are the VCD stiffness and VCD damping coefficients, respectively at a given temperature and frequency. When the connecting steel elements are more rigid, the effective VCD response is essentially defined by equation (1), and when the connecting steel elements are more flexible, the VCD hysteresis tends to flatten and dissipate less energy. As discussed previously, when the VCDs are used in areas of large seismic demands, a structural "fuse" element can be introduced to reliably cap of the load introduced to the structure and the designer

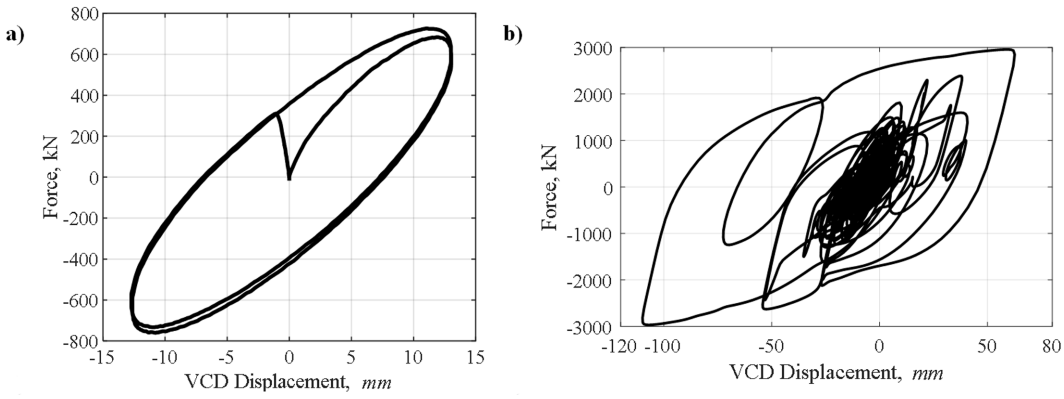


Figure 5. Sample full-scale VCD test results from test setup 2: a) harmonic tests at frequency of 0.1 Hz and b) test result of a scaled MCE level Tohoku 2011 ground motion (M9.0).

can capacity design the other structural elements for those maximum expected forces. Figure 5b) shows the experimental results of a simulated Tohoku 2011 ground motion (M9.0) scaled up to beyond the target maximum considered earthquake (MCE), and applied to the Megatall building described in Section 2.3. In this detail, a steel shear critical link element was incorporated in the connections in series with the VE damper element. The resulting hysteresis is a Viscoelastic-Plastic response where the maximum load introduced to the capacity protected structural elements is capped off, as presented in Figure 5b). With ductile detailing of the steel link, it is possible to achieve significantly more deformation compared to a typical RC beam member. For loading scenarios with a significant multi-modal response, it is common to model the system using a Generalized Maxwell Model (GMM), which consists of multiple springs and dashpots in parallel and series. This can be incorporated in typical commercial software packages such as Perform-3D and ETABS (Pant et al., 2015 and Pant et al., 2017).

1.2.2. VCD System Behavior and Impact in Tall Building Dynamic Response

It is well documented that tall buildings can have amplified dynamic wind and seismic response due to their relative flexibility and their low damping, which actually decreases with height (CTBUH, 2008 and Smith et al. 2010). Added damping can have substantial impact on reducing the response of buildings to wind and seismic loads (Vickery et al., 1983 and Hanson and Soong, 2001).

For wind applications, distributed viscoelastic damping is effective in reducing frequent wind vibrations, increasing occupant comfort and reducing drifts as well as reducing wind loads, as the VE material is stable over all loading levels and frequencies of vibration. For seismic applications, VCDs reduce drifts and accelerations as well as building seismic loads. In addition, VCDs are inherently more resilient than the structure they are replacing and as such the anticipated damage and downtime under earthquake loads can be reduced significantly with VCDs, especially when they are configured in locations where the concrete elements they are replacing are expected to sustain severe damage under seismic loading.

1.2.2.1. Coupling Beam Configurations

Coupling beams are commonly used to couple large structural walls, increasing the stiffness of lateral load resisting systems and, under large seismic loads, provide stable energy dissipation. VCDs replace coupling beams with a gap between the slabs and the VCDs to accommodate movement. Generally, VCDs are made of VE damper panels that are bolted on to steel W-sections which are then anchored into the walls (see Figure 1a)). When VCDs are used in the core they add damping to all lateral modes of vibration, including torsion and higher modes.

1.2.2.2. Outrigger Configurations

Outriggers represent an effective strategy to stiffen structures laterally, by connecting the core to external gravity columns. This is highly effective for wind applications as it reduces overturning moments and drifts. In seismic applications the system can reduce drifts and overturning moments, but generally increases core wall shear and requires careful detailing at the outrigger levels. The inelastic response of conventional outriggers is also difficult to predict and could result in unexpectedly large forces applied to the exterior outrigger columns. VCDs are used in outriggers by extending out the RC walls and attaching VCDs from the outrigger to the external columns (see Figure 1d). When VCDs are configured in the outriggers, damping and restoring coupling forces are efficiently added to the sway modes of vibration while the maximum forces produced are well controlled and can be adequately designed for.

2. Impact Studies on Tall Buildings Equipped with VCDs

The impacts of VCDs used in tall buildings equipped with VCDs to mitigate wind and or seismic response are

presented in the following examples. The first is a wind critical 66-story building in downtown Toronto, the second is a performance-based seismic and wind design development consisting of 4 towers of 41, 43, 45 and 49-stories, respectively, in Manila, Philippines and the third a performance-based designed 630-meter Megatall building in Southeast Asia.

2.1. 66-Story Wind-Sensitive Building in Toronto

Yonge College (YC) Condominiums is a slender (11 to 1 slenderness) 66-storey residential tower in downtown Toronto, designed by Read Jones Christofferson in Toronto and peer reviewed by Magnusson Klemencic and Associates. The slenderness led to large frequent lateral wind vibrations, which cause occupant discomfort. The VCD was selected based on the developer's mandate to maximize sellable space within a prescribed height.

In the slender direction, the lateral load resisting system consists of two primary coupled RC shear walls, along with an RC core and columns (see Figure 6). Wind tunnel studies, conducted by RWDI, revealed that the building would require a supplemental damping system to increase the damping in the first mode of vibration to improve the level of human comfort for frequent motions. The design team considered the distributed Viscoelastic Coupling Dampers (VCDs) or a bi-level Tuned Sloshing Damper (TSD) tank to mitigate the frequent wind vibrations. The building developer and design team undertook a detailed technical and financial comparison. The developer selected the VCD because it was integrated within the structure and resulted in an additional 5,000 square feet of usable penthouse real estate as well as the fact that there were no requirements for tuning, monitoring or maintenance with the VCD system.

The structure utilized 84 identical modular Viscoelastic coupling damper panels, produced by Nippon Steel USA and 3M. Two-VE damper panels were bolted to cast-in-place steel embeds. A total of 42 VCDs were used on 21 levels of the structure (see Figure 6). Temporary steel channels were used during casting to ensure correct VE damper placement during construction. When the building envelop was completed, a small crew of three ironworkers, removed the channels and installed the VE damper panels with a slip-critical bolted connection, followed by drywalling.

The wind tunnel studies required 0.9% supplement damping in the fundamental mode of vibration. Each VE damper panel has nine (9) VE material layers, each 5 mm thick, with the VE material bonded between the steel plates. VE dampers were modeled as springs and dashpots in parallel, along with the connecting steel elements and configured into the Engineer of Record's (EOR) ETABS models. The added damping was assessed using free vibration analyses by inputting a lateral push to the building, releasing the load, and measuring the reduction in amplitude over multiple cycles of vibration.

In addition, RWDI provided realistic wind load time-histories based on their wind tunnel tests for the key wind directions (angles of attack) for the design of the building. The time-histories were applied to an ETABS model with the VCDs modeled as nonlinear links. One such time-history response for the governing design direction of attack for a 1 in 10 year storm is shown in Figure 7. As can be seen the drift profile is reduced as well as the peak lateral acceleration due to the added VCDs.

The dynamic characteristics of the structure were monitored with accelerometers as the project progressed during construction as well as localized displacement measurements of the dampers in order to study the robustness of the damping system and to compare the as-built building behavior to the structural models. The building was monitored during a service level wind storm (5-year return period). The total damping in the building slightly exceeded the design target levels.

2.2. Performance-Based 4-Tower Seismic and Wind-Critical Development in Southeast Asia

A 4-tower Japanese-inspired development was designed by ARUP and Nikken Sekkei, in an area of the world with some of the largest wind (typhoon) and seismic hazards. A typical design in this region is to conduct a conventional code-based design for wind using a combination of American and local codes and non-prescriptive

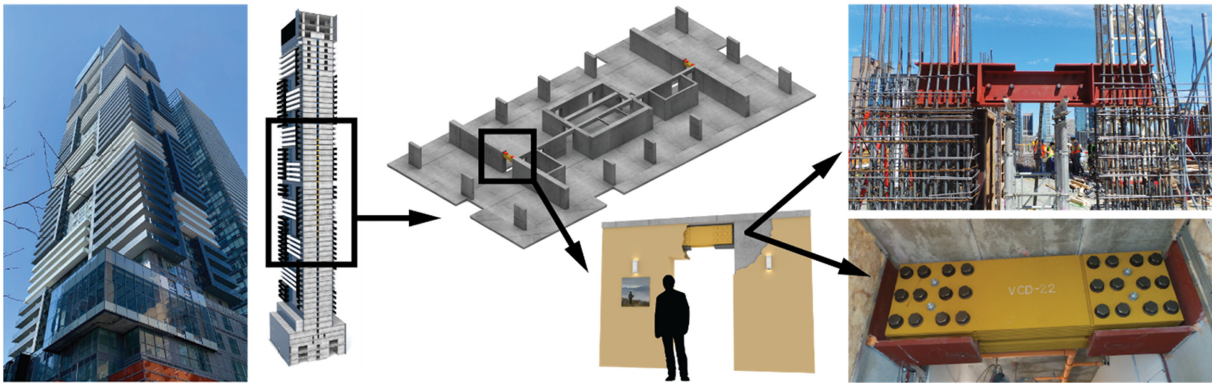


Figure 6. VCDs in Yonge College Condos (Photographs by M. Montgomery).

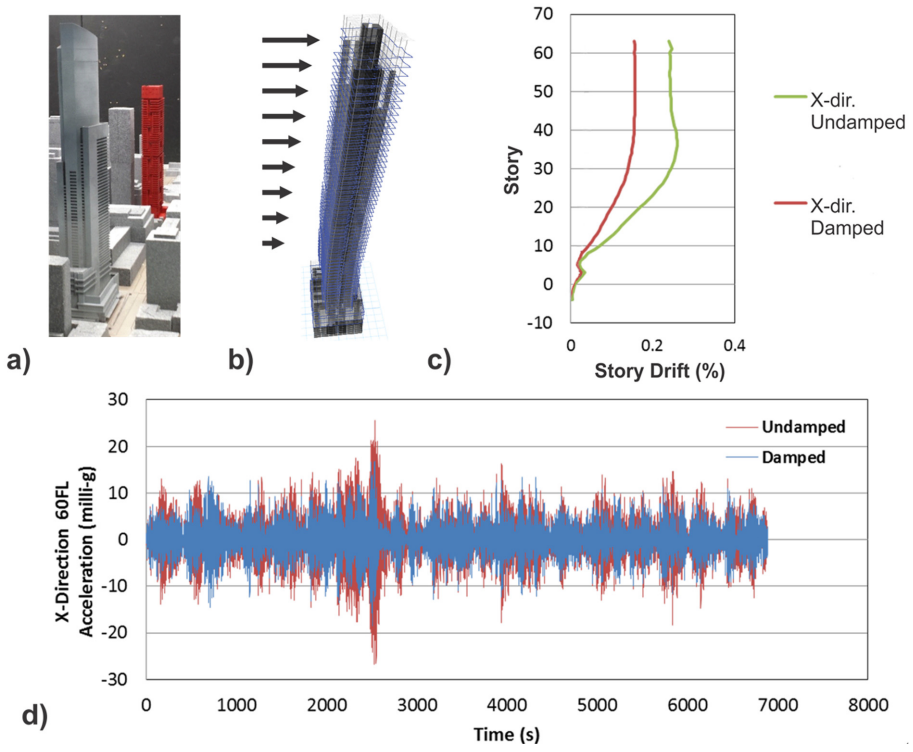


Figure 7. Wind tunnel time-histories: a) rigid pressure model, b) ETABS model deformed shape, c) story drift profile and d) acceleration response (photograph by Michael Montgomery).

performance-based design using the PEER-TBI (PEER 2010) and LATBSDC (LATBSDC 2014) guidelines. In addition, because this was a high-end Japanese inspired development, certain design criteria were based on Japanese requirements as well. These towers were sensitive to both wind and earthquake loads because of their slender profiles. The development consisted of 42, 44, 48 and 51-storey towers, interconnected by a five-story retail development above parking levels (see Figure 8).

An important challenge for the design team was to limit the wind drifts as the original conventional design of each of the four towers exceeded the prescribed drift limits, ranging from 20% to 80% above the prescribed limits in the short directions of the towers (see Figure 9a)). The final design had VCDs introduced in each of the towers connecting the RC flag walls to the columns, in a RC flag wall scheme, which is common in the region to reduce the wind drift demand on taller buildings. The connecting steel elements generally followed the requirements prescribed in ASCE-341 seismic details. The flag walls and columns

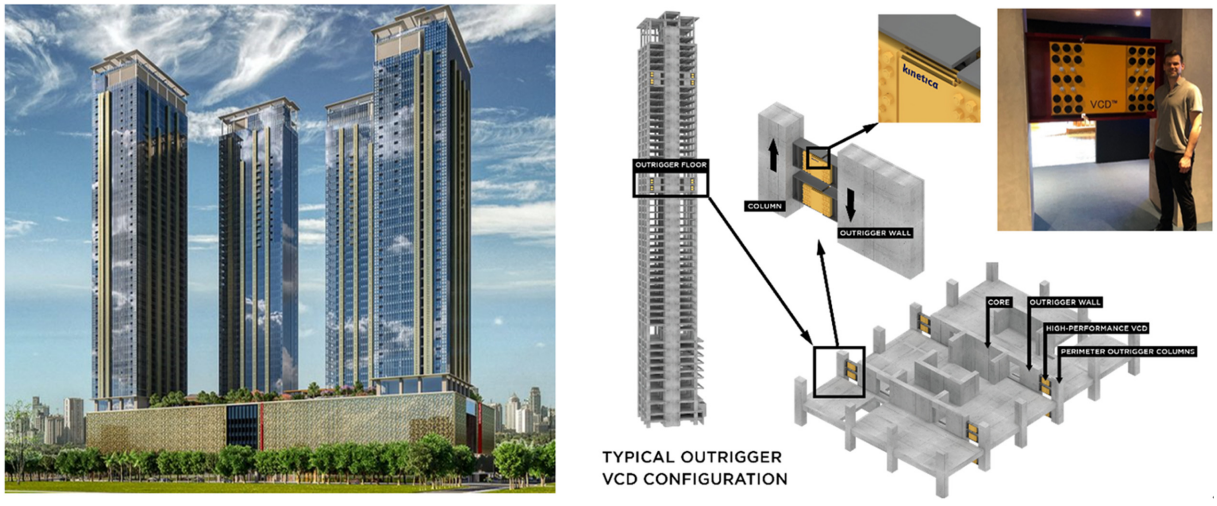


Figure 8. 4-Tower Performance-Based Seismic and Wind Design Project (Photograph by Michael Montgomery).

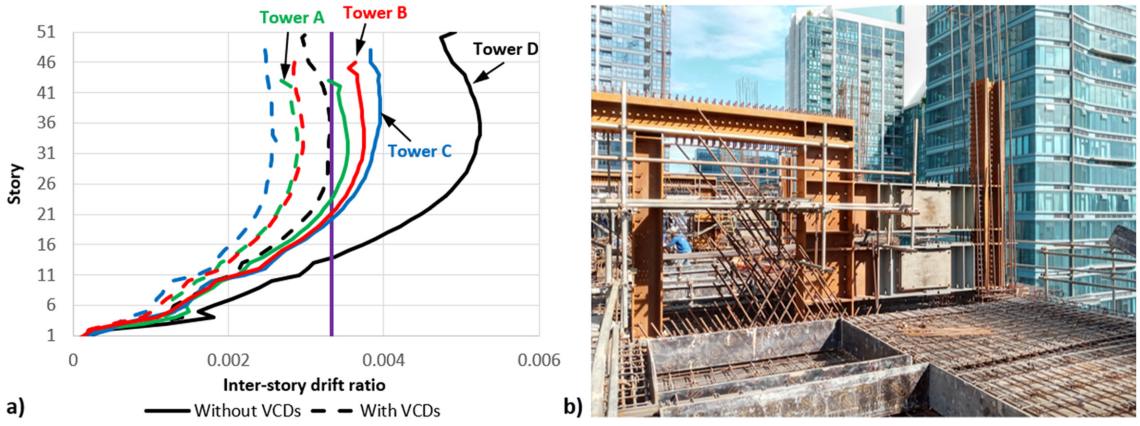


Figure 9. a) Interstory-drift ratio for 1 in 50 year loads and b) Flag-wall structural steel at the VCD (Photograph by Jose Velchez).

were capacity-designed to accommodate expected over-strength forces in the ductile members. A slotted connection was provided to allow for differential vertical settlement between the core and the columns, if required.

The dampers were modeled in ETABS for the wind and SLE models and in Perform-3D for MCE models. Under more frequent windstorms (1 in 1 yr, 1 in 10 yr and 1 in 50 yr), the dampers added significant damping (supplemental damping of 2-5% for the primary modes of vibration for the towers) which reduces the lateral accelerations and drifts substantially. Under design level wind or service level earthquake events, when the structure is intended to respond linearly elastic or essentially elastic, loads were reduced, which resulted in structural efficiencies. Under more extreme events such as Maximum Credible Earthquakes (MCE), the ductile steel connecting elements were designed to form a "structural fuse" to protect columns and flag walls. Figure 9b) shows some of the flag wall steel prior to the concrete walls being cast at the flag wall level with VCDs.

The design team considered four outrigger schemes for the tower which are described and compared below:

Conventional RC outrigger flag wall scheme – this is a commonly used structural system locally, whereby large exterior columns are connected to the core using RC walls and diagonally reinforced RC beams which span the corridor. The diagonally reinforced RC beams are designed to act as structural fuses and the remainder of the flag wall is designed to remain elastic under earthquakes. This scheme had the largest earthquake demands on the adjacent structural members and had the most flag wall stories.

Viscous damper outrigger flag wall scheme – The RC flag wall scheme is designed the same as the conventional flag wall scheme with large connections blocks to connect viscous dampers to columns. Viscous dampers had the lowest earthquake demand on adjacent structural members, but required more flag wall levels and dampers than the VCD scheme in order to meet the wind drift requirements. In addition to the large connection blocks, the viscous dampers required inspection corridors adjacent to the walls to monitor the viscous dampers for wear or leakage, reducing the sellable space.

Buckling restrained K-brace outrigger scheme – BRBs were designed to connect on a diagonal between the RC core and the outrigger columns. The design consisted of a K-brace scheme over four stories at an outrigger level, with large horizontal members to resolve the horizontal forces at the connection points of the diagonally orientated BRBs. Because of the K-brace schemes considered, it required reconfiguring the corridors which was not optimal from and architectural point of view and required more outrigger levels than any of the other three options which reduced the sellable space. In addition, because of the relatively large stiffness of the, BRB scheme had similar large earthquake demands on the structure when compared to the conventional RC outrigger flag wall scheme.

VCD outrigger flag wall scheme – The RC flag wall scheme was designed the same as the conventional flag wall scheme and VCDs frame directly from the columns to the flag walls. The VCDs were designed with structural fuse elements to provide a reliable force cap-off for earthquakes. The VCD solution had the best wind performance (lowest drift and force demand) because of it's damping and stiffness and had similar earthquake performance to the viscous damping solution. It resulted in the most sellable space for the client because it required the least levels of flag walls and had no requirements to inspect the dampers or maintain them over the life of the structure.

The VCDs were chosen for this project, as they had the best overall wind and seismic performance as well as the least impact on the sellable space.

2.3. 630-meter MegaTall Seismic-Critical Building in Southeast Asia

A 630 meter Megatall building in one of the most

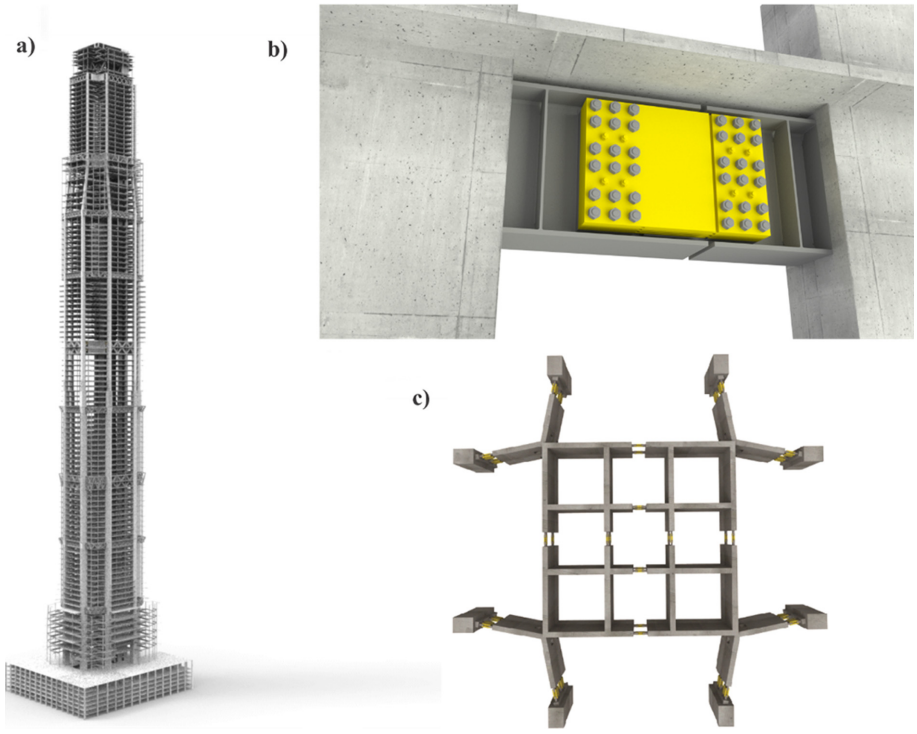


Figure 10. a) Isometric view of the megatall building considered, b) a typical core-wall VCD and c) typical outrigger configuration with the VCDs.

extreme seismic zones in the world was designed with VCDs for seismic performance improvements (Figure 10). The design of the building was governed by seismic loading and was designed with a non-prescriptive performance-based approach by structural engineering designers Thornton Tomasetti and PT Gistama. The 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. In addition, a secondary lateral load resisting system consisted of a mega-frame with super columns and belt trusses as well as an outrigger system.

An alternate design was developed whereby VCDs are placed in multiple outriggers and replacing about 60% of diagonally RC coupling beams in the core throughout the height of the building (see Figure 10). Four VCDs were placed at each outrigger location. Each VCD was modeled in ETABS for SLE and wind models and Perform-3D for Maximum Credible Earthquake models in the same manner as described in the previous project above. The supplemental distributed damping amounted to about 8% added distributed damping for the two sway directions and significantly more for higher modes. This is estimated to reduce the dynamic wind response (lateral accelerations and displacements caused by the resonant loading) by more than 50% compared to the undamped building.

The design response spectra corresponding to various hazard levels are plotted in Figure 11a) and the seven scaled MCE time-histories in Figure 11b).

Changes in the maximum values of peak response

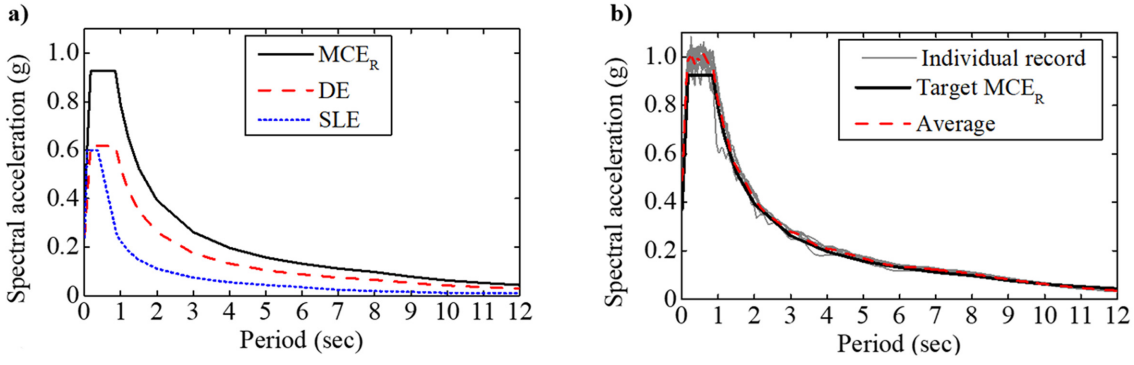


Figure 11. a) Design response spectra and b) comparison of individual scaled ground motion maximum direction response spectra as well as their average with the risk-targeted MCE spectrum.

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%

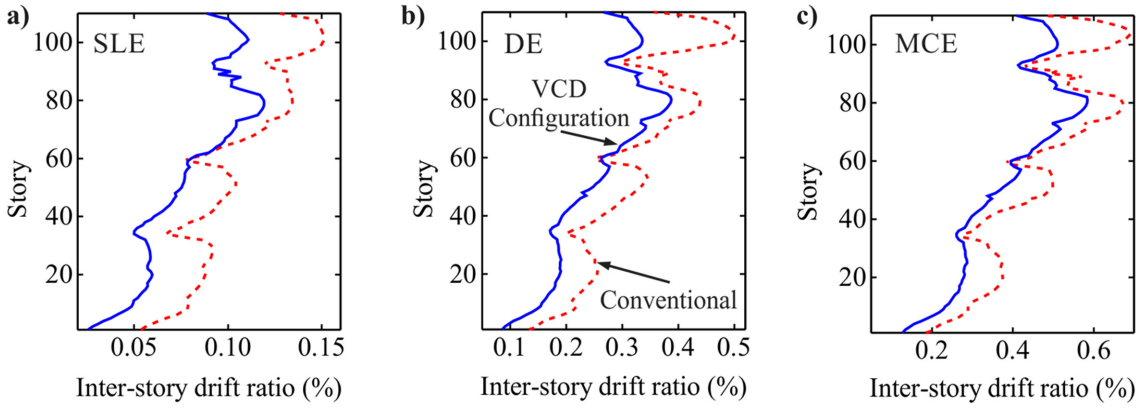


Figure 12. Median values of Y-direction inter-story drift ratios.

indicators of the VCD building along the X- and Y-directions are compared to the conventional building in Table 1. The Y-direction was a focus of this work as it was the governing direction. The Y-direction peak inter-story drift ratio and peak floor acceleration profiles are plotted in Figures 12 and 13, respctively, for the SLE, DE, and MCE_R level ground motions. As can be seen in Figures 12 and 13, 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 the coupling beam plastic rotations, and the core wall shear forces and bending moments, are plotted for the Y-direction of the building in Figure 14. In the conventional design, many RC coupling beams suffer plastic rotations in excess of 1% to 2% (Figure 14a), which correspond to minor damage and moderate damage, respectively (Naish et al. 2013). In the VCD structure, plastic rotations are all under 1%, indicating that the coupling beams will not require repair. As can be seen in Figure 14b), reductions in shear forces for the VCD structure throughout the height of the building indicating that the thickness of the core wall can

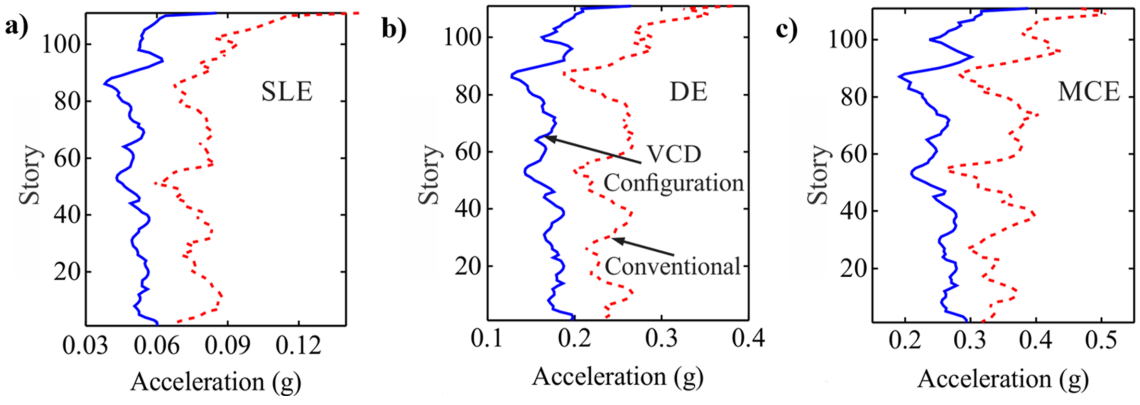


Figure 13. Median values of Y-direction peak absolute floor acceleration.

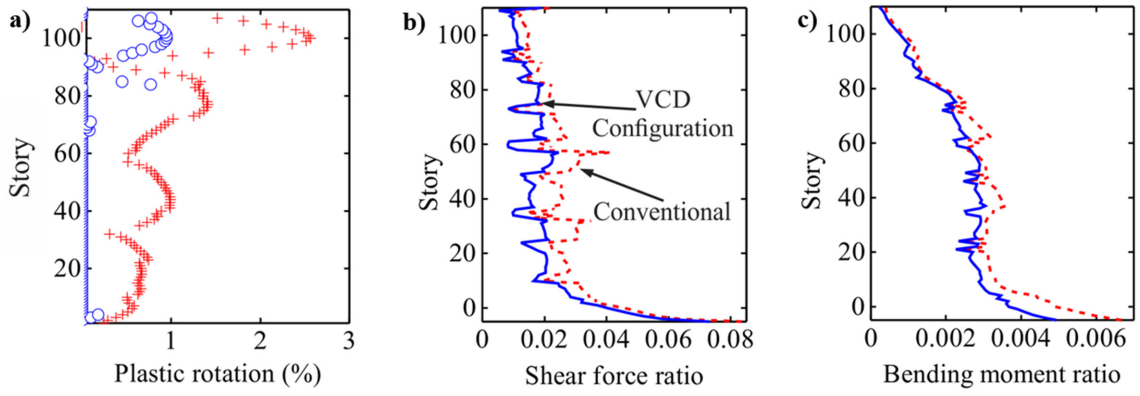


Figure 14. Median values of Y-direction peak response indicators for MCER level ground motions: a) coupling beam plastic rotation, b) core wall shear force ratio and c) core wall bending moment ratio.

be reduced in the damped building leading to a possible up-front cost reduction (Figure 14b). Similarly, the base bending moment is reduced significantly which results in a reduction in the cost of the foundation and mat thickness (Figure 14c).

An intensity-based financial loss and downtime estimation was carried out for the conventional as well as the VCD building using the SP3 Program (SP3 2016) and the results are shown in Figure 15 and Figure 16. Typical non-structural and structural elements were included in the analysis. More information on the loss and downtime estimates can be found in Pant et al. (2017). As observed in Figure 15, the VCD design results in reductions in repair costs for all components of the building. In the VCD 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. More substantial benefits of the VCDs are more evident at lower but more frequent seismic events. Direct repair costs are only a small fraction of the financial loss that will be incurred due to downtime (Figure 16). It can be seen from Figure 16 that the VCD building suffers smaller downtimes for all levels of earthquake hazard (i.e., re-occupancy, functional recovery, and full recovery)

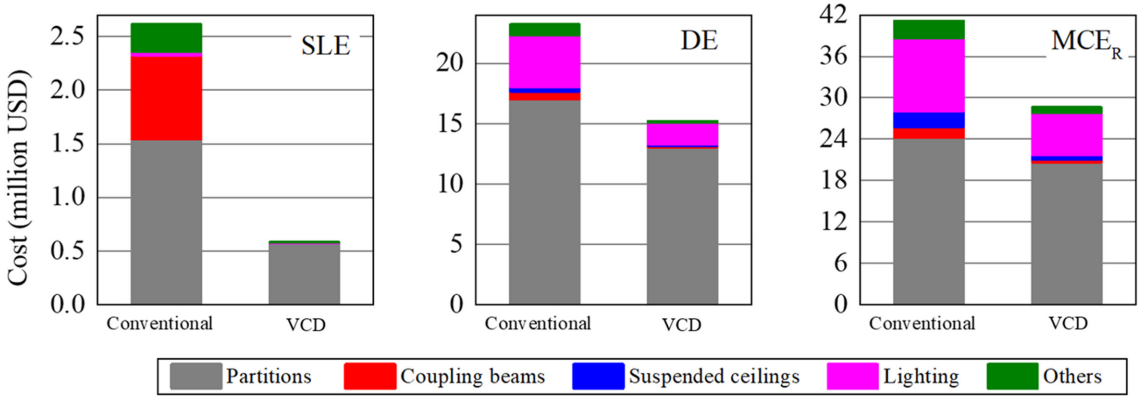


Figure 15. Direct repair costs of conventional and VCD buildings for different seismic hazard levels.

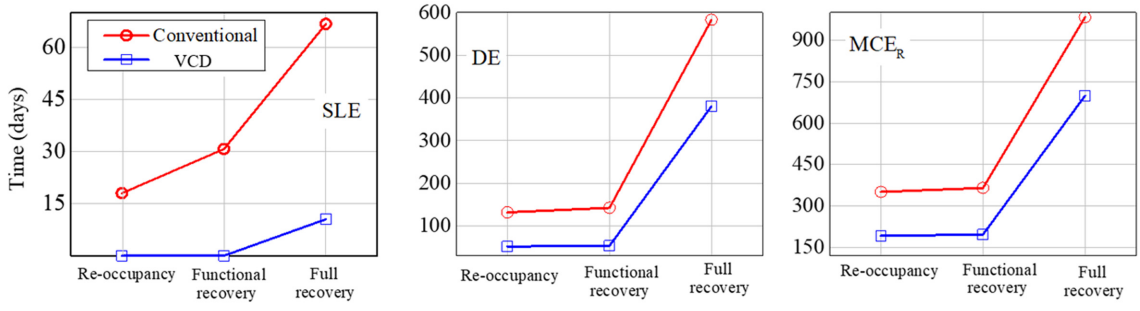


Figure 16. Recovery times evaluated using REDi methodology for conventional and damper building for different hazard levels.

compared with the conventional building. 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. Notable are the results for the SLE events which show that the conventional building which requires downtime of about 1 month for functional recovery, however can maintain its functionality immediately following an SLE level event in the VCD structure.

The performance improvements for the VCD structure are substantial. In addition financial benefits including a net cost reduction estimated at $20 Million (including the cost of the VCDs) and a 6 month reduction in construction time were also estimated by the design team. This is due to reduced construction complexity, reduction of 3,000 tonnes of steel, 500 tonnes of rebar, 15,000 m^3 of concrete and a reduction of 2 meters in the foundation slab thickness.

Conclusions

The Viscoelastic Coupling Damper (VCDs) system has been described in this paper. Its use and configurations within coupling beams and outrigger systems for both wind and seismic performance enhancement have also been described and full-scale test results have been presented. Studies on three building projects were summarized: i) for a wind-critical 66-story building in Toronto, ii) for a wind- and seismic- performance based design for a four tower development in Southeast Asia and iii) and for a seismic-critical 630 meter Megatall building in Southeast Asia.

For the wind-critical tall building in Toronto, VCDs replaced a number of RC core beams in order to increase the level of inherent damping for wind serviceability requirements. The developer selected the VCDs for the project after a detailed technical and financial analysis considering TSDs and VCDs. The VCDs allowed the developer to maximize revenue on the project and eliminated the need for long term maintenance, tuning or monitoring with a tuned system.

For the wind- and seismic-performance based design of a 4-tower development, the VCDs were utilized in a RC flag-wall configuration for enhanced wind and seismic performance. The VCD design was compared to a conventional RC flag wall system, a viscous-damped flag wall system and a K-brace BRB outrigger configuration connecting the RC core to the exterior columns.

For the 630-meter Megatall building in Southeast Asia, the VCDs increased the seismic performance of the building for all hazard levels compared to the conventional structure. The VCDs delayed damage in the structure as well as non-structural components for all seismic hazard levels. The core coupling beam damage would be eliminated by removing the RC coupling beams and by replacing them with high-performing VCDs. The VCD structure also was estimated to be $20M less expensive (including the cost of the VCDs) and was estimated to reduce construction time by 6 months.

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