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Seismic and Wind Performance of Tall Reinforced Concrete Buildings in Vancouver with Outrigger Viscoelastic Coupling Dampers (VCDs)

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ABSTRACT

Reinforced Concrete Coupled Core walls are a commonly used structural typology throughout the world, including the Greater Vancouver area. This structural system is convenient for tall multi-storey residential buildings because the structural core can be used to house elevators, stairwells, services and provide egress routes. Reinforced Concrete Coupled walls can be detailed to be very ductile and can serve as the primary seismic lateral load resisting system with gravity columns over the rest of the floor plate area. As residential buildings are built taller, wind loads begin to increasingly affect the lateral load resisting system design either because of human comfort concerns under frequent winds, or large design loads under ultimate level windstorms. Recent research has shown that the dynamic response of these buildings can be significantly improved with added damping. Viscoelastic Coupling Dampers (VCDs) were developed to add supplemental damping to structures through the shearing of solid viscoelastic material (VEM) layers bonded to steel plates, which are anchored to reinforced concrete structural elements through steel embeds. When the VEM is sheared, it adds supplemental damping to the structure at all displacement amplitudes, which reduces both wind and seismic loads. It has been effectively implemented in reinforced core wall structures and outriggers coupling concrete cores to external columns in many regions of the world both for enhancing the response to large wind loads and seismic hazard. This study investigates the benefits of using the VCD system in a 47-storey tall case study building in downtown Vancouver. The main focus of this paper is to examine how the addition of one or more damped VCD outrigger levels can allow this building to be built taller without changing its original structural design. This study evaluates the performance of this building with a single core and varying damped outrigger designs. It discusses the reduction in wind lateral accelerations and loads from damping and demonstrates the increased resilience using the VCD for seismic loading. These findings further highlight the benefits of using supplemental damping to overcome the design challenges of structures in the greater Vancouver area, and for tall buildings that face high levels of both wind loading and earthquake hazard.

Keywords: Outrigger damper, tall buildings, Viscoelastic Coupling Dampers, Wind and Earthquake design, damped outriggers.

1 INTRODUCTION TO TALL BUILDINGS IN VANCOUVER - WIND AND SEISMIC PROBLEMS

The city of Vancouver is one of the major growing cities of North America, the third largest city in Canada and in the Pacific Northwest after Seattle and Portland. The metropolitan area of Vancouver, which includes the cities of Surrey and Burnaby, has seen a population growth of more than 10% in the last five years [1]. Tall building typologies are the preferred structural system adopted widely to accommodate the widespread of population growth in this city, with more than a twofold increase in the tall building stock during the past 20 years [2]. The city of Vancouver is on the west coast of Canada and is prone both to strong earthquake shaking and high intensity windstorms, which creates important design challenges for these tall structures [3].

The current design practice for tall buildings in Vancouver consists of reinforced concrete coupled shear wall structures surrounded by perimetral gravity columns [3]. This building layout maximizes the architectural space, concentrates the elevators and main structural elements of the building in the core of the structure, and offers versatile architectural spaces that can accommodate many residential units in condominium buildings. As these core wall buildings grow taller, wind design considerations can become challenging to meet. These generally consist of limiting both the maximum drift to 0.2% and the maximum floor accelerations to 18 milli-g for frequent windstorms (1–10-year return periods), as well as designing for strength to ensure that there is little to no damage (essentially an elastic response) for design level windstorms (1-50-year return period events) [4]. Frequent winds can impose roof accelerations that induce levels of human discomfort that range from a minor annoyance to severe motion sickness, which in some cases can lead to the lateral design being governed by service level wind induced vibrations. The current design solution to mitigate wind vibrations consist of increasing the stiffness of the building by augmenting the size of the structural elements or adding a secondary lateral resistant system such as an exterior moment frame or outriggers, reducing the number of floors plates, and/or adding a damping system to the building to mitigate dynamic vibrations. Each of these solutions can affect the project programming and therefore require careful consideration by the engineering team [6 - 8].

The high seismicity of the metropolitan Vancouver area imposes challenges to the seismic design that must be addressed in parallel to the wind design of these tall buildings [9]. The stringent wind design criteria for these tall towers leads to large structural members that can transmit significant ductile forces to the main structural system of the building for maximum credible earthquakes (MCE levels with a return period of 1 in 2500 years). In addition, little to no damage is expected for frequent level ground motions, which can result again in larger structural elements that inevitably affect the structural behaviour of the building and the net cost of the project. Recent research suggests that the dynamic response of tall buildings is greatly dependent of damping, and that both earthquake and wind vibrations can be effectively controlled by adding supplemental damping, rather than increasing the overall stiffness of the structure [10 - 12]

The use of embedded solid viscoelastic (VE) dampers is increasingly being. considered as an attractive design strategy for controlling both wind and seismic induced vibrations in tall buildings [13]. The broad deformation amplitude efficiency range of VE dampers allows for an integrated earthquake and wind design solution strategy where the supplemental damping is providing benefits for all dynamic loads. The Viscoelastic Coupling Damper (VCD) is an effective technology for the implementation of VE damping in tall buildings [14]. These coupling dampers replace common coupling structural elements in tall buildings such as lintel beams and outriggers; they are installed seamlessly within the core wall system of the budling, and therefore they optimize the architectural space of the project.

In this paper, the effectiveness of the VCD system is studied for a conventional 47-storey tall core wall building in downtown Vancouver. This building was increased in height without modifying its lateral resistant system and damped VCD outriggers were added to control the response of the structure through added damping rather than modifying the lateral system of the building. The application of outrigger VCDs are introduced in this paper, and the benefits of this system are explained through this case study building including its low invasiveness, the advantage of inserting the dampers at mechanical or elevator levels, and the option of increasing the architectural sellable space and revenue on the project.

2 INTRODUCTION TO THE VCD SYSTEM AND VCDs ON OUTRIGGERS

Viscoelastic Coupling Dampers (VCDs) were developed over the past few decades at the University of Toronto to increase the level of inherent damping of tall building structures [15]. VCDs are configured in lieu of traditional reinforced concrete (RC) coupling elements such as lintel beams and outriggers without occupying any sellable architectural space. These coupling dampers are composed of multiple layers of viscoelastic (VE) high damping material bonded in between steel plates and bolted to steel embeds or end-plate beams anchored to conventional RC walls or columns. VCDs add damping under all levels of wind vibrations, increasing occupant comfort and reducing both drifts and design loads. For large inelastic demands that are common during major earthquake events, the VCD has capacity designed yielding elements capable of limiting the forces transmitted to the structure and dissipating energy during severe ground shaking. Following a maximum level earthquake event, yielded fuses can be inspected and easily replaced reducing downtime and repairs to tall buildings. Figure 1 presents the VCD in common coupling locations (lintel beams and outriggers), a description of the VE damper panel, and the intended hysteretic behaviour that is characterized by an elastic response for frequent vibrations and a viscoelastic-plastic response for ultimate loads.

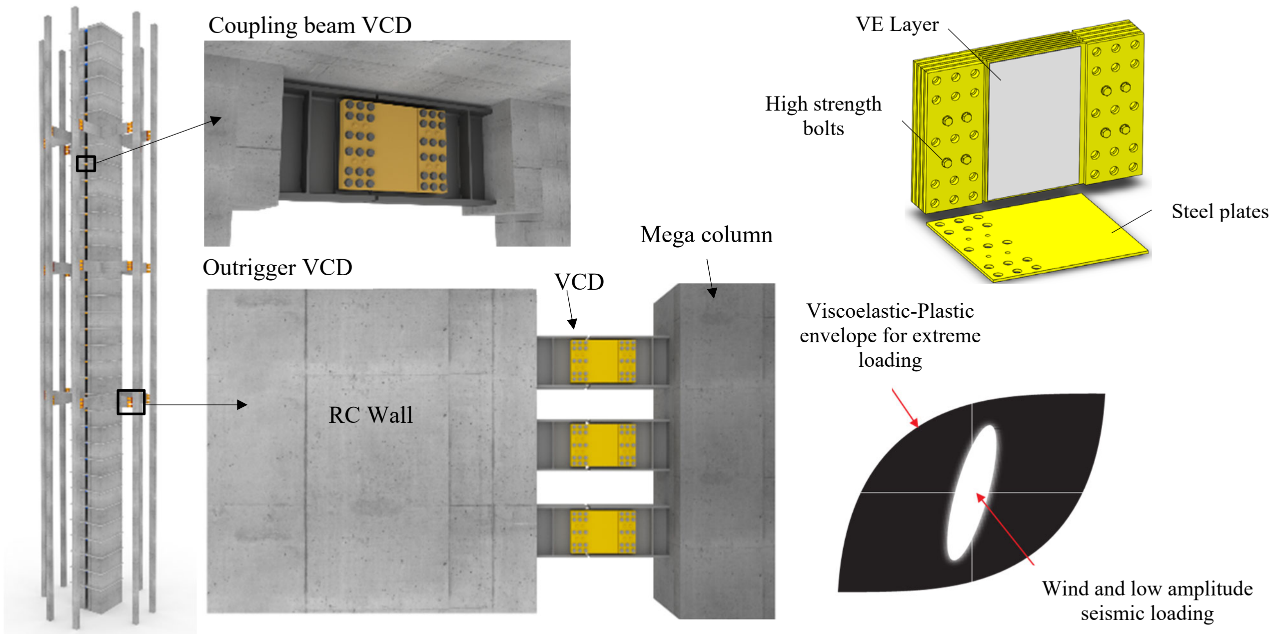

Figure 1. (a) Damped VCD high-rise building, (b) Outrigger detail, (c) VCD and VE panel

Viscoelastic materials provide both velocity and displacement restoring forces when they undergo relative displacements in between structural elements such as shear walls and outrigger in tall buildings. The VCD can be characterized using a simple Kelvin Voight model, where the force $F_{VCD}(t)$, at a time t, can be represented using Equation 1 [16].

$$F_{VCD} = K_{VCD}u_{VCD} + C_{VCD}\dot{u}_{VD} \tag{1}$$

Where K_{VCD} corresponds to the elastic stiffness of the damper and C_{VCD} is the viscous coefficient that can account for the energy dissipation of each VE layer. u_{VCD} and $\dot{u}_{VCD}$ are the velocity and displacements of the group of VE layers when they experience shear deformations. For maximum level earthquakes, the dampers are equipped with hysteretic shear link elements that can activate at higher loads to absorb the energy from the ground shaking and limit the loads transferred to adjacent structural elements such as outrigger walls and mega columns. The following section will illustrate these outrigger details.

The outrigger VCD damped configuration (Fig. 1) is an effective solution to mitigate vibrations, because it combines the added stiffness and stability offered by outriggers, and it increases the inherent low damping of tall buildings. In addition, this damping system can be inserted in only few locations along the height of building that are seamlessly integrated in the main lateral structural system without affecting the architectural layout of the building. Even though there are optimal locations for the installation of outriggers based on numerical analysis of tall buildings equipped with VCDs [17, 18], the outrigger floors are often limited by architectural constraints. For core wall tall buildings in Vancouver, the roof level is the preferred location to install outrigger VCDs (commonly known as a hat-outrigger), because typically this floor houses mechanical and elevator equipment, which is a convenient location to store and install these dampers. If more outrigger levels are required to bring the structure to meet code design requirements (wind and earthquake roof accelerations and inter-storey drifts), another VCD floor can be inserted along the height of the structure, preferably at mechanical or service maintenance floor levels.

3 CASE STUDY BUILDING

The effectiveness of the VCD system for wind and earthquake applications is presented in this section for a 47-storey coupled shear wall tall building project located in downtown Vancouver. Building CW47 (concrete wall – 47 stories tall) was designed according to the National Building Code of Canada [4] and the Canadian Concrete Design Handbook (CSA-A23) [19]. This tower has a total height of 141 m with in-plan dimensions of 25 m by 31 m. The main lateral resistant system is composed of ductile shear reinforced concrete cantilever walls in the *y* direction and coupled shear walls in the *x* direction. The main concrete core is surrounded by squat columns that mainly carry gravity loads. The slabs are made of 8-inch posttensioned concrete members. The concrete strengths vary from 70 MPa at the base of the building dropping to 50 MPa at the upper levels. Figure

2 shows the elevation of the building as well as description of a typical floor plate. This tower was modelled in the commercial structural engineering software ETABs [20]. The structural walls of the building were modelled using a wall-shell element that can capture the out-of-plane behaviour of the wall, bending in three directions and bidirectional shear. The coupling beams and columns were modelled using one-dimensional beam elements, and the PT slab was modelled using a shell slab element with 8” of thickness. Live gravity loads consisted of 1.92 kPa from levels 1 to 45, and 0.9 kPa at the roof level, and dead superimposed loads were 0.96 kPa from levels 1 to 45 and 3.56 kPa at the 46 and 47 levels.

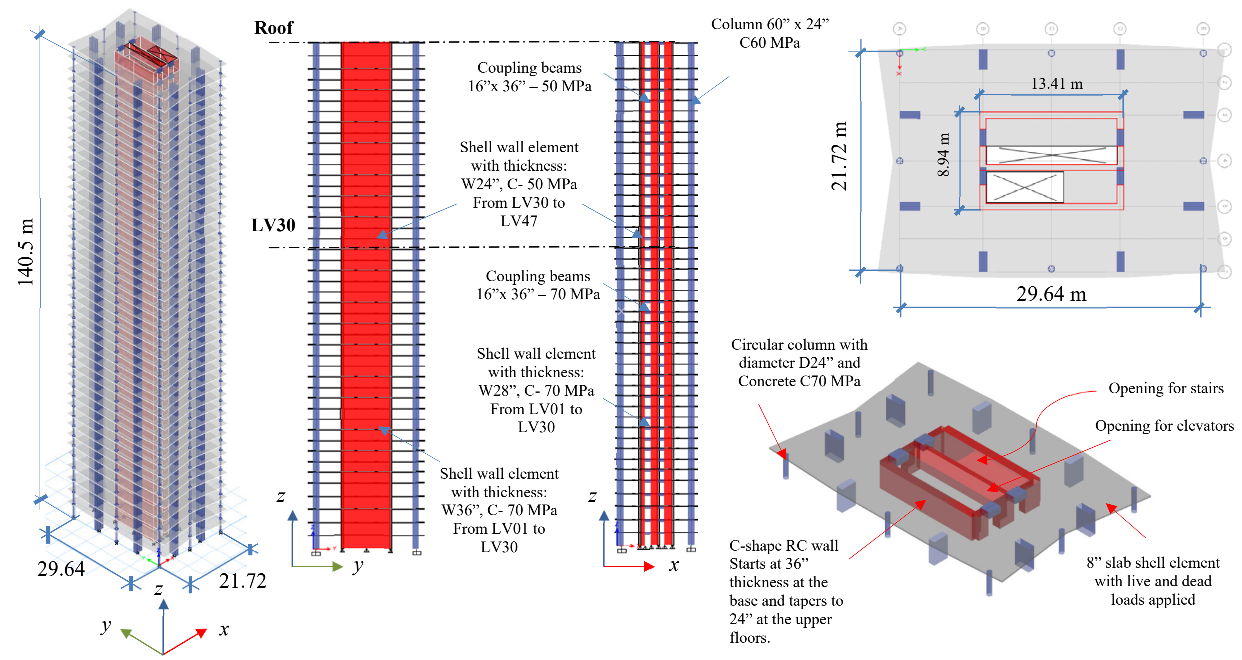

Figure 2. (a) Description of building CW47

The design of the lateral resistant system was governed by earthquake forces. Lateral vibrations for this building due to service level wind loads also complied with code provisions with maximum roof accelerations below the 18 milli-g residential limit (NBCC [4]). Figure 3 shows the wind and earthquake design forces and the earthquake drifts for this building.

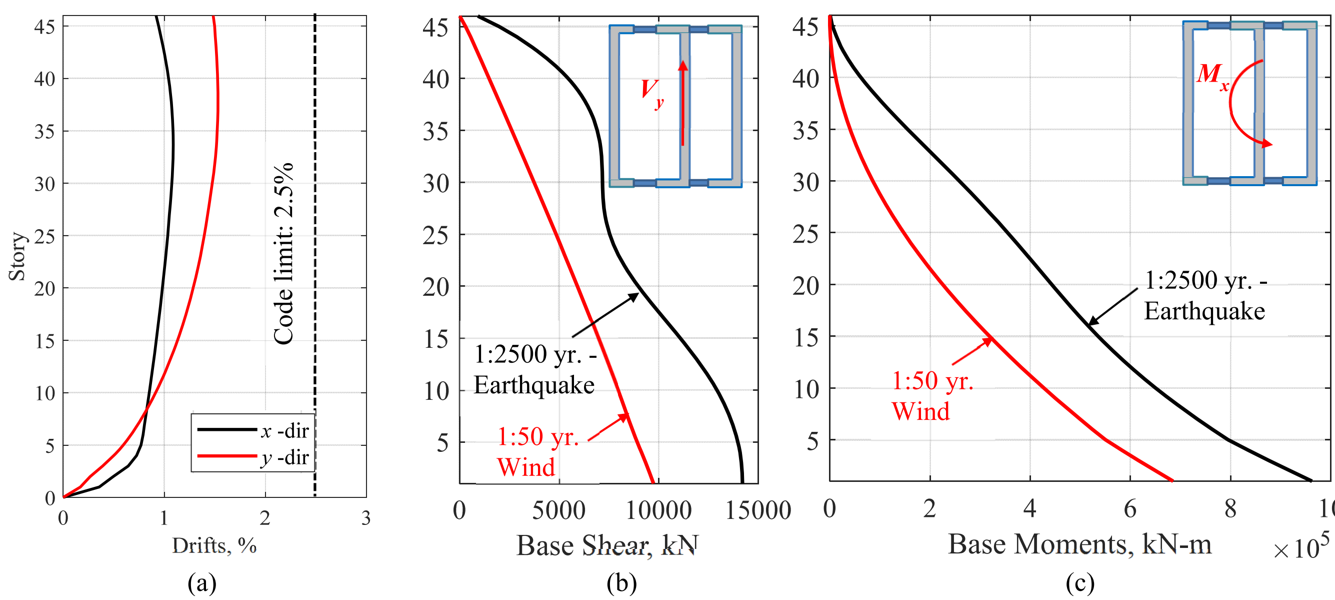

Figure 3. Structural response for CW47 (a) inter-storey drifts for seismic design loads (b) maximum base shears and (c) base moments for both wind and seismic loads.

The building developer was interested in increasing the height for building CW47 and its number of storeys after adding a damping system without changing the original structural design. Outrigger VCD schemes for this building were studied to maximize the architectural space of this building, and the main results from this study are presented in the following section. This study is used to investigate how added outrigger damping systems in one or more locations along the height of the building can result in more efficient designs.

4 CASE STUDY RESULTS AND VCD DESIGN

Building CW47 was increased in height while adding VCD outrigger levels. The methodology that was followed in this process consisted of adding floors in small increments to the baseline building (CW47) and evaluating the maximum wind service level limit state (SLS) wind vibrations (maximum roof accelerations and inter-storey drifts) until these buildings no longer met the design requirements. Figure 4 illustrates the progressively higher structures that were considered, and Table 1 shows the dynamic properties of these buildings alongside the maximum roof SLS acceleration, which shows that towers above 57 storeys do not comply to the residential roof acceleration limit from NBCC: 0.2% and 18 milli-g, drift, and roof acceleration, respectively. VCD Outriggers were added to these taller structures (above 57 stories) to bring back their structural response to code requirements.

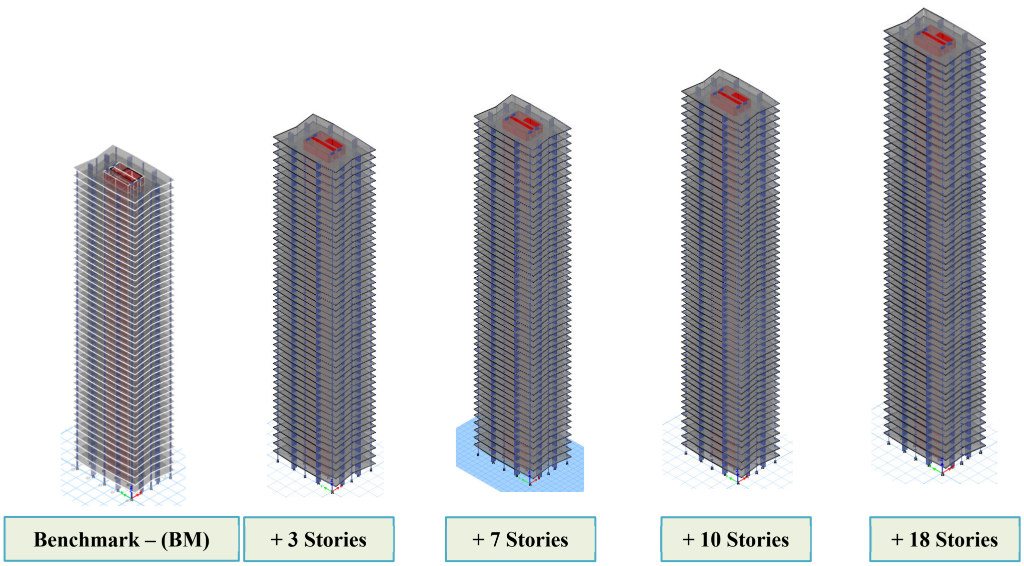

Figure 4. Progressively higher structures considered in this study.

Table 1. Dynamic properties of structures considered and maximum roof accelerations. Roof accelerations were estimated using the online NATHAZ (Natural Hazard) aerodynamic data base [21]. U_H is the design velocity at the height of the building.

Stories	Height (m)	U_H (m/s)	T_n (s)	Max roof Acceleration NATHAZ (milli-g)
BM - 47	140	28.76	4.60	8.65
50	151	29.50	5.27	12.42
52	155	29.76	5.56	14.16
54	166	30.44	6.16	17.7
57	**170**	**30.69**	**6.87**	**19.7**
65	195	32.12	9.01	28.45

Two new buildings were selected with 10 (CW57) and 18 (CW65) additional stories, respectively to the original base structure. The height of the baseline building was increased without modifying the lateral system, and damping outriggers were added to control the response of the new structures such that they met all design requirements. Building CW57 and CW65 were modelled using ETABs and the original structural detailing of the reinforce concrete shear walls, columns, coupling beams and slabs were replicated for the additional floors considered. The VCD locations for these group of buildings were limited to the least intrusive floor-levels, and therefore outriggers were only installed at the roof and mid-height maintenance levels for these buildings. In order to diminish the invasiveness of the damping system, only three VCDs were installed at each of the outrigger flag walls, thus limiting the height of the outrigger detail to less than two consecutive floors. Several VCD layouts were studied to enhance the dynamic behaviour of these buildings, and the optimal configuration is presented in Figure 5 for both the hat outrigger and the two outrigger schemes that were added to the base line structure CW47, as well as to buildings CW57 and CW65. Further details of the VCD design optimization process can be found in [18].

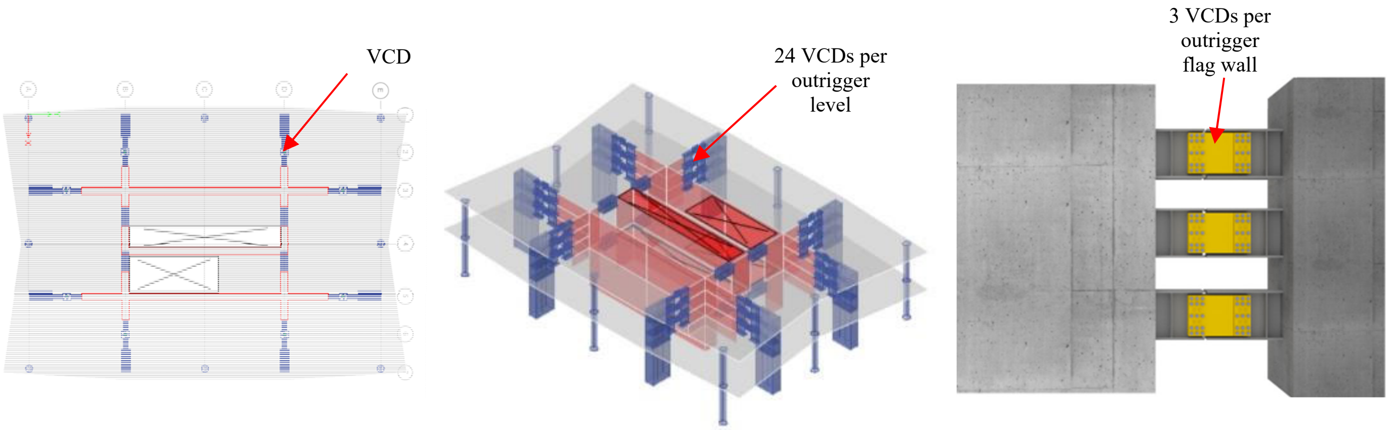

Figure 5. (a) outrigger VCD detail for Vancouver buildings considered in this study (CW47, CW57 and CW65).

The dampers were modelled using the Generalized Maxwell Model [17, 18]. This model consists of a series of springs and dashpots that can capture the frequency dependency of the viscoelastic material. Figure 6 shows a schematic of the model selected for the VCD assembly considering a reference temperature of 25 degrees Celsius. DBE earthquake experiments are also presented in this figure to illustrate the numerical capabilities of this GMM model to capture the multifrequency response of this building. Further details of this GMM model and the related full-scale experiments can be found in [18].

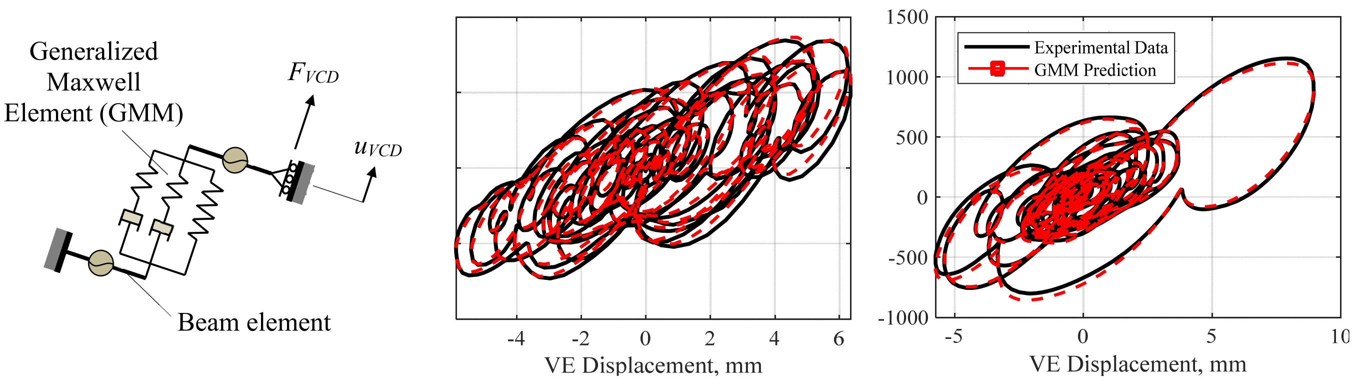

Fig. 6 – (a) Schematic of the numerical model of the VCD and (b)-(c) validation of the model based on full scale tests of a VCD in a 50-story building subject to Design level earthquake- 1979 Imperial Valley and 1999 Chichi Earthquakes, respectively.

Free vibration analyses were carried out in ETABs to calculate the total amount of damping provided by each of the outrigger schemes in the two fundamental modes of vibration. Figure 7 shows the dynamic properties of each of the structures, the supplemental damping from VCDs, and the maximum roof accelerations for each of the VCD solutions considered. Analyses results demonstrated that the SLS wind response for all buildings equipped with either a hat-outrigger (single outrigger level at the top of the building) or a two-outrigger scheme had improved inter-storey drifts and roof accelerations when comparing to the bare structures without VCDs, because of the supplemental damping and stiffness. As an example, Figure 7b shows that the maximum roof acceleration of the bare structure for building CW57 is 19.65 milli-g (yellow box in Fig. 7b), which is higher than 18 milli-g (the residential limit specified by the NBCC). However, after adding a hat outrigger, the maximum roof acceleration in this tower diminishes from 18.12 milli-g to 9.35 milli-g with a hat single outrigger (green box in Fig 7b), and to 6.87 with a two-outrigger scheme respectively (as shown by the green boxes in Figure 7b). Furthermore, the fundamental period of this building decreases from 6.87 to 6.02 seconds demonstrating the additional stiffness provided by the outrigger VCDs. Similar conclusions can be derived for building CW65, as presented in Figure 7c, the maximum roof acceleration significantly decreases from 28.45 to 17.12 and 13.33 milli-g for the hat outrigger and two outrigger schemes respectively. Note that damping provided in the figure is supplemental damping provided from the dampers.

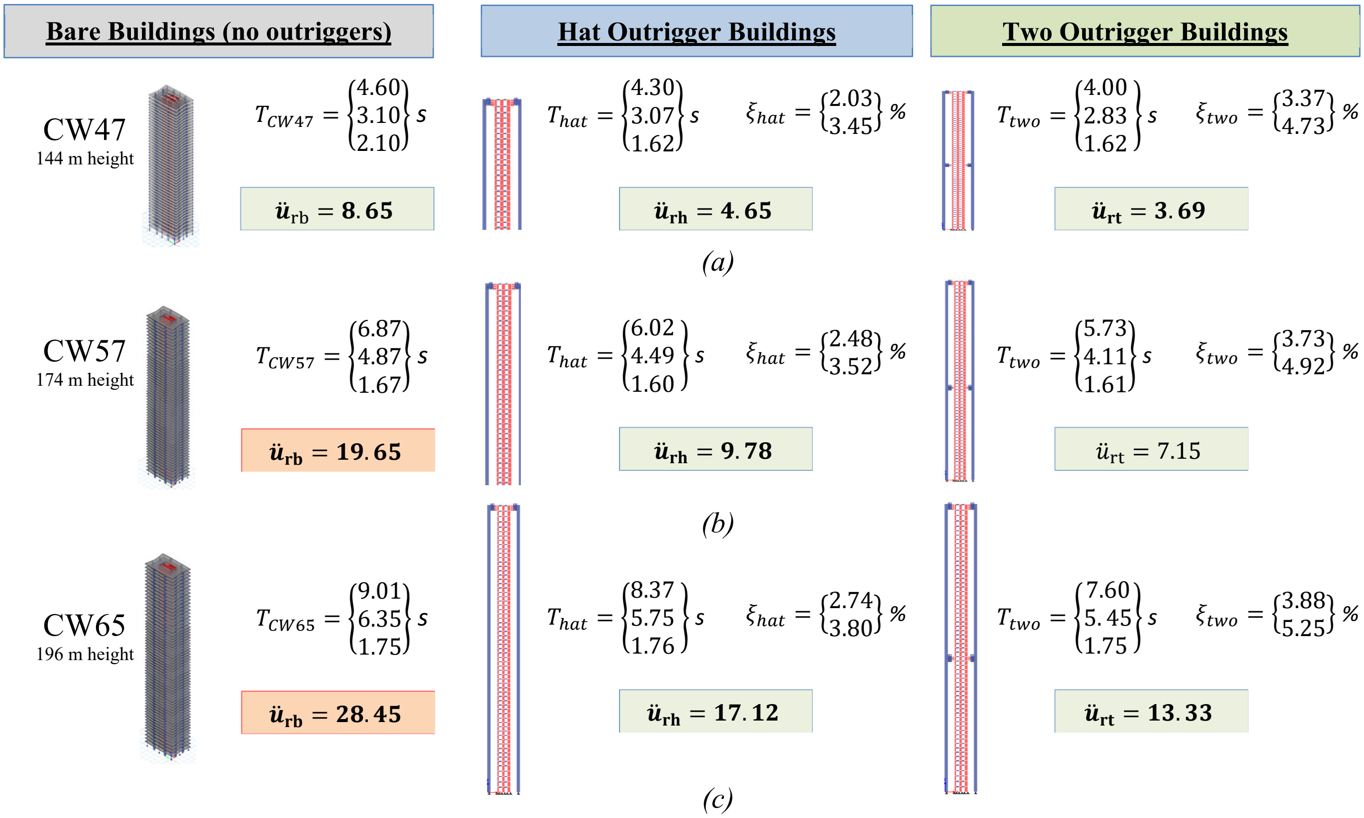

Fig. 7 – Outrigger VCD solutions for CW-Vancouver family of buildings. Roof accelerations $\ddot{u}_r$ (milli-g), structural periods T, and supplemental damping ξ for "b" bare "h" hat outrigger and "t" two outrigger buildings for (a) CW47 (b) CW57 and (c) CW65 towers. The roof acceleration for the benchmark buildings were calculated assuming a damping ratio ξ = 1.5% (for SLS wind loading). All damping ratios presented in this figure represent the supplemental damping provided by the VCD system.

Figure 8 presents the maximum inter-storey drifts for each of the buildings considered (CW47, CW57 and CW65) alongside the response of the outrigger VCD solutions. In Figure 8, the black solid plots represent the inter-storey drift response of the bare buildings (without outrigger VCDs), and the blue and green plots show the improved outrigger VCD response for the single hat-outrigger and the two-outrigger scheme buildings, respectively. As presented in Figure 8b -8c, for both CW57 and CW65 buildings, the bare structures do not comply with the code drift limits. The drift response of all buildings significantly improves when using either a single or a two-level outrigger VCD scheme, allowing all VCD outrigger buildings to comply with the SLS drift criteria of 0.2%. Event though all outrigger buildings complied to the SLS design criteria (maximum roof accelerations were below 18 milli-g, and all inter-storey drifts were below 0.2% as presented in Figure 7 and 8 respectively), the ULS wind forces of these structures were above the capacity of the structural members that had the same detailing as the baseline tower CW47; these forces will be presented in Figure 9 and will be discussed next.

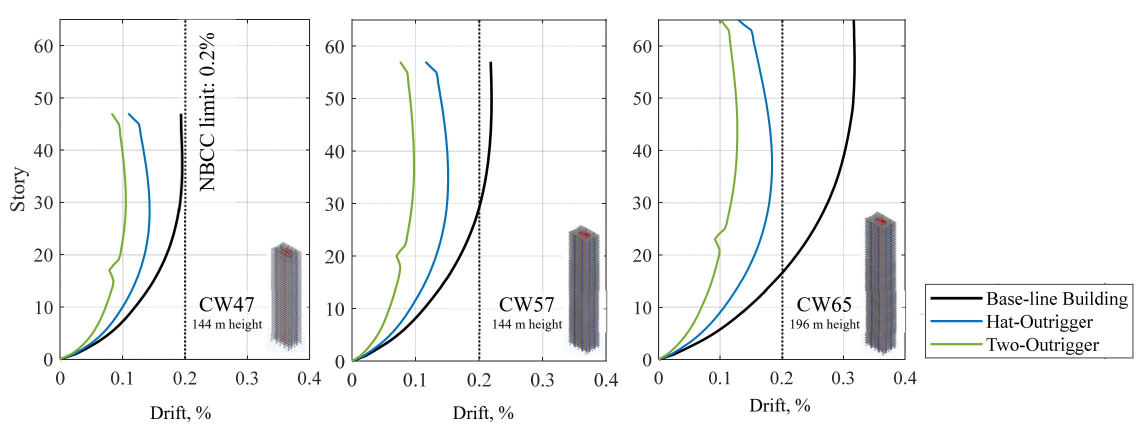

Figure 8. SLS inter-storey drift response for CW-Vancouver buildings

The supplemental damping provided by the VCD solutions were used to calculate the maximum forces experienced by the main structural members of the lateral resistant system of these buildings. Figure 8 presents the maximum force carried by the most loaded coupling beam and pier for each of the buildings considered (CW47, CW57 and CW65). In Figure 9, the response of the bare building is shown in black (core wall buildings without VCD outriggers), the response of these buildings equipped with only one hat outrigger in blue, and the response of the two-outrigger buildings in green. The dotted green curves show the capacity of the main structural elements (main coupling beam and pier) from the original structural design from tower CW47.

The shear forces carried by the south-east coupling beam (Figure 8a) for buildings CW57 and CW65 were above the capacity of these beams from the baseline (CW47) structural design. However, when evaluating these forces for building CW57 equipped with a hat outrigger (Figure 8b), they comply with the capacity of the original design (green dotted line). Furthermore, the structural reinforcement and detailing of this coupling beam can be replicated in the upper additional floors without changing any of the original lateral design of building CW47. This is not the case for building CW65, as it is presented in Figure 8b, because the forces in this coupling beam are above the baseline capacity from tower CW47. However, when adding a second outrigger level to building CW65 (Figure 8c), the forces dropped substantially allowing this building to comply with the capacity of the original design from building CW47. Similar conclusions can be drawn for the main pier of this building, as presented in Figures 8d-8f.

The force levels presented in Figure 8b and 8e indicate that the hat-outrigger building CW57 complies with the capacity of the baseline building CW47 (green dotted line), and therefore ten additional floor plates can be safely added to the baseline tower when a single outrigger level is utilized at the top of the building. Building CW65, however, cannot work with only the hat outrigger level, but a two-outrigger scheme enables the building to have adequate performance while keeping the initial structural layout for the main piers and coupling beams unchanged as presented in Figure 8c and 8fd. In summary, a hat outrigger VCD scheme allows for the increase of the initial building height by an additional 10 stories, and a two outrigger VCD solution allows for an 18-storey height increase.

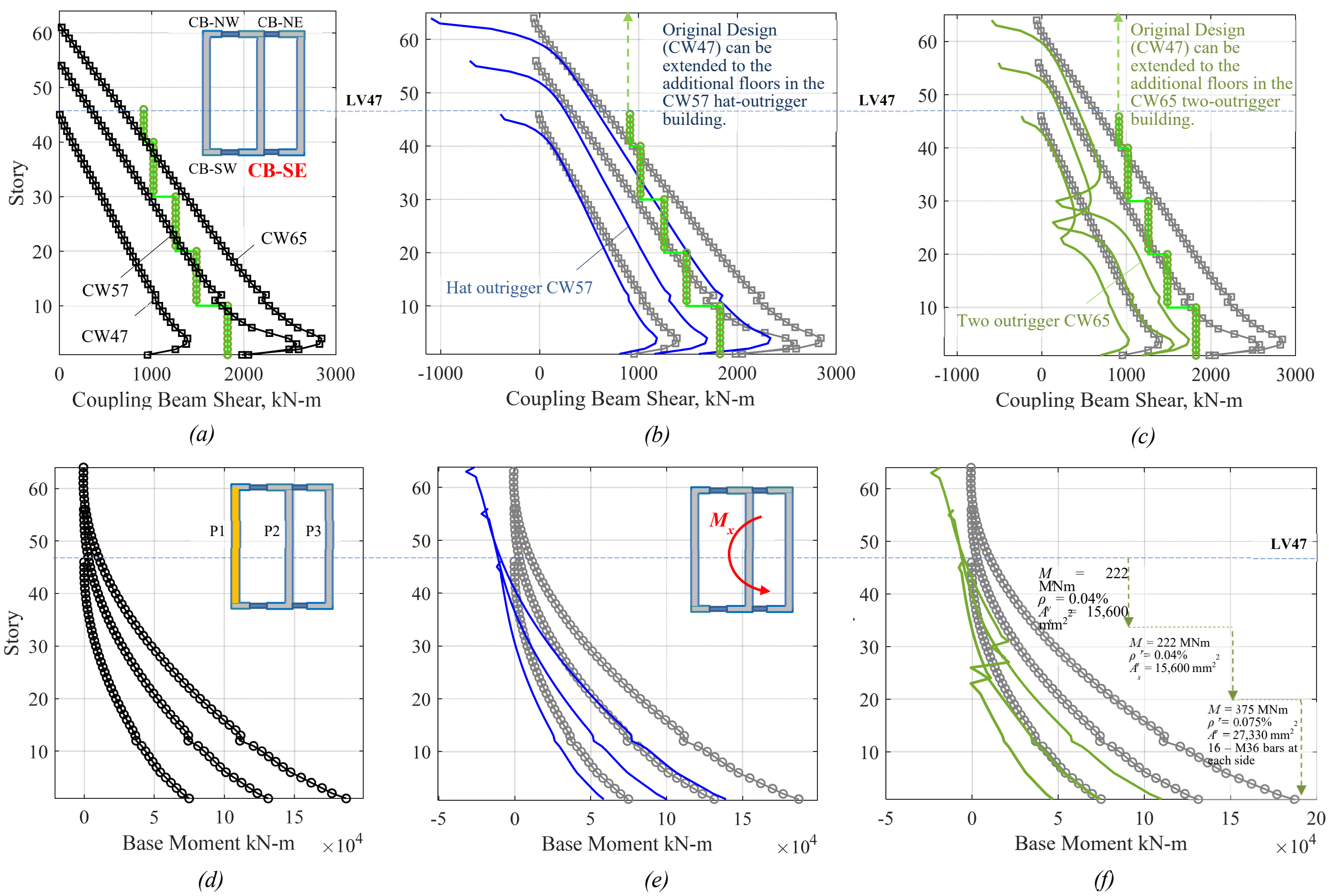

Fig. 9 – Comparison between bare structures and outrigger VCD solutions for critical structural elements: (a) South east coupling beam (CB-SE) shears for buildings without VCDs (b) CB-SE shears for hat outrigger buildings (c) CB-SE shears for two outrigger buildings (d) Pier 1 (P1) moments for bare buildings (e) P1 moments for hat outrigger buildings (f) P1 moments for two-outrigger buildings.

5 CONCLUSIONS

The benefits of using the VCD system in a tall building located in Vancouver were presented in this paper. Building CW47 was defined based on a typical design of a commonly used structural typology in downtown Vancouver. The building owner was interested in increasing the height of this building while adding a damping system without altering the lateral resistant design of this structure. The VCD system was studied as a means of achieving this goal, by using a layout that is minimally intrusive to the building's programming since the damping elements are installed seamlessly at the roof and the maintenance-service level of the building. This study showed that a single outrigger level with a total of 24 VCDs can increase the height of the baseline building by 10 stories, while adding a secondary outrigger level at mid-height with 24 additional VCDs can lead to an increase in height of 18 stories without modifying the structure. The VCD system allowed the taller towers to meet serviceability requirements in accordance with the NBCC, optimized the architectural sellable space that would have been used otherwise by a vibration absorber (such as a tunned mass damper), and did not create abrupt changes of stiffness that are common for other earthquake ductile systems such as large steel trusses and buckling restraint braces installed as outriggers, as observed in the moderate changes that the damped outrigger buildings presented in their dynamic properties with respect to the bare buildings. This paper illustrates the benefits of using VCDs for outrigger systems in tall buildings, however, further improvements could be derived in terms of enhanced construction times, reduced downtimes and repair after major earthquake events, and improved resilience as presented in [14, 15 and 18].

Acknowledgements

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