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Viscoelastic coupling damper tests for outrigger systems in supertall buildings

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ABSTRACT

Viscoelastic Coupling Dampers (VCDs) were developed to add distributed supplemental damping to all modes of vibration of coupled shear wall high-rise buildings. This paper presents results of the early stages of a full-scale experimental program of a damped outrigger VCD configuration designed to enhance the dynamic behavior of supertall buildings. The outrigger VCD consists of two viscoelastic (VE) damping panels bolted to structural steel sections. VE damper panels are made of multiple high-damping VE layers bonded to steel plates. The VE material adds damping and stiffness to the structure under wind and design level earthquake loading. Under extreme earthquake loads, connecting shear steel fuses are capacity designed to protect the structure from damage, thus exhibiting a viscoelastic-plastic response. Component-level experiments were conducted on two sets of VE panels with different damping and stiffness properties. Full-scale VCDs coupling the core wall and the outrigger column of a megatall building were tested in double curvature with realistic boundary conditions emulating a real building application. Preliminary viscoelastic tests displayed stable hysteretic behaviour for targeted service level wind and seismic loading as well as for ultimate level wind loading, covering a wide range of both amplitude and duration of wind and earthquake vibrations. Preliminary full-scale experiments demonstrated that the outrigger VCD is a promising high-performance energy dissipation device, capable of enhancing the dynamic behaviour of supertall buildings

Keywords: Full-scale testing, Outrigger damper, Supertall buildings, Viscoelastic coupling dampers, Wind and Earthquake loading.

INTRODUCTION

Modern high-rise building design is moving towards slender and taller structures, and these buildings are dynamically sensitive to both wind and earthquake vibrations. For supertall (over 80 stories) and megatall buildings (over 110 stories), design guidelines recommend a combination of lateral resistant systems such as reinforced concrete (RC) coupled shear walls and outriggers. In order to ensure appropriate seismic and wind behaviour for these buildings, performance-based methodologies are followed, and resilience goals are considered in their design. Low financial losses and repairs (out-of-service time) are often targeted after major earthquake events for these tall buildings [1,2].

The lateral resistant system of these tall buildings is designed to withstand windstorms and earthquakes for an accepted return period. Current design solutions to enhance the dynamic response of tall buildings are based on vibration absorbers, reducing the building height, and increasing the stiffness of the structure lateral resistant system; however, these alternatives have negative financial consequences [3-5].

Vibration absorbers, such as tuned mass dampers (TMDs) and sloshing mass dampers, are installed in the upper levels and consist of a heavy mass tuned to vibrate with the natural period of the structure [6]. TMDs are an effective damping solution to reduce service level wind vibrations; however, due to the inherent changing properties of reinforced concrete over the life of the structure, they require monitoring and maintenance. In addition, they often decrease the building revenue by occupying the most valuable architectural space of the structure. For major earthquake events, these devices have a lock-in-place mechanism to avoid amplifying structural demands in the building, thus providing no dynamic response enhancements to ultimate seismic loads. In most cases, the wind and earthquake design of tall buildings is achieved independently with this system.

Outrigger systems are a viable solution to increase the lateral stiffness of tall buildings. Robust coupling elements, such as deep RC beams and large trusses, tie the main RC core wall system to perimeter mega columns while increasing the overall building stability and overturning resistance [7]. Recently, the structural engineering community has adopted braced outrigger solutions such as buckling restrained braces (BRBs) for seismic applications, and fluid viscous brace dampers to mitigate wind vibrations [8, 9]. Large BRBs can increase the stiffness and, in some cases, avoid the use of wind vibration absorbers for buildings located in combined wind and earthquake zones [10]. Although these solutions may provide an effective wind and earthquake design, BRBs transmit large forces to their connecting elements while total construction time and costs are affected by the installation of these large members in the structure.

Recent research has shown that the dynamic response of these buildings is greatly dependent on damping, and that small increments in their inherent damping, using multimodal supplemental damping devices, can lead to a vast improvement of the structure dynamic response, and a reduction of the project total construction cost [11-14]. A new damping technology, the Viscoelastic Coupling Damper (VCD) has been developed at the University of Toronto [15] to add distributed damping throughout the height of tall buildings, and to enhance their wind and earthquake resilience. VCDs consist of two viscoelastic (VE) damping panels bolted to structural steel sections. VE damper panels are made of multiple high-damping 3M VE material layers bonded to steel plates (Fig. 1). 3M VE material adds damping and stiffness to the structure under wind and low amplitude earthquake loading. Under extreme earthquake loads, connecting shear steel fuses are capacity designed to protect the structure from accumulating damage. VCDs can replace common lateral-resistant structural elements such as outriggers and RC coupling beams in coupled shear wall buildings. In addition, VCDs can be designed with replaceable connection details, thus accelerating repairs and reducing out-of-service time of tall buildings after major earthquakes. Moreover, VCDs allow for a multi-hazard (wind and earthquake) design solution for tall buildings.

Montgomery and Christopoulos [16] validated the experimental behaviour of full-scale VCDs for coupled shear wall systems. Mckay-Lyons et al. [17] and Montgomery [18] conducted extensive non-linear numerical analyses of tall buildings equipped with VCDs and reported improved performance in all engineering demand parameters (drifts, RC core base shears, and accelerations) for design level vibrations, and increased seismic resilience with less structural damage for maximum credible earthquakes. Pant et al. [19] conducted an analysis of a megatall (630 m tall) building using a combination VCDs replacing RC coupling beams and outriggers and found meaningful financial savings, when compared to the conventional building, and significant reductions in financial losses and downtimes for ultimate level seismic events (considering state-of the-art-financial loss assessment methodologies).

This paper outlines the features of the damped outrigger VCD system and the early stages of its full-scale experimental validation. Eight full scale VCDs were designed for two targeted projects: four specimens for a 280 m tall building located in a high wind and high seismic risk zone, and four more for a 630 m megatall building in a high seismic risk area. A large range of dynamic, and quasi-static testing protocols have been proposed to evaluate the VCD performance for outrigger systems. Preliminary experimental results for service limit earthquakes and wind testing protocols confirmed the intended VCD viscoelastic behavior for frequent levels of vibration. This paper presents preliminary experimental results of an extensive testing program currently underway at the University of Toronto.

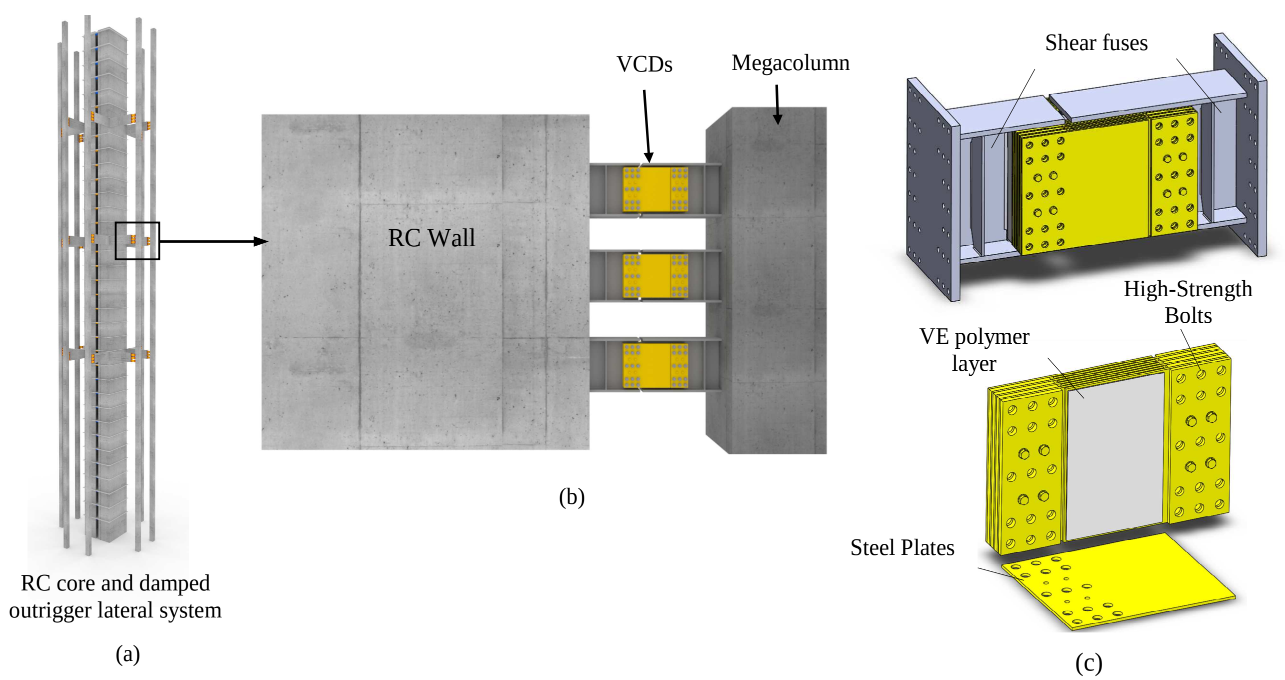


Figure 1. (a) Damped VCD high-rise building, (b) Outrigger detail, (c) VCD and VE panel

OUTIGGER VISCOELASTIC COUPLING DAMPER

Viscoelastic coupling dampers connect the RC core walls of tall buildings with perimeter mega-columns. When supertall buildings are subject to lateral loads, VCDs deform predominantly in shear providing both displacement and velocity (viscoelastic) restoring forces to the structure. The dampers are located in the main structural lateral resistant system of the building and optimizes the sellable architectural space, while providing supplemental damping to all sway and torsional modes of vibration.

For service level wind and earthquake vibrations, as well as design level wind storms, the damper response is solely viscoelastic. The structural deformations only take place in the viscoelastic layers, while keeping the connecting elements elastic without accumulating any damage. For major earthquake events, built in shear fuses activate and the damper response becomes viscoelastic-plastic (Fig. 2). Outrigger VCDs have a built-in lock up mechanism that limits the VE elastic deformation, while additional inelastic demands are sustained by the shear link fuses.

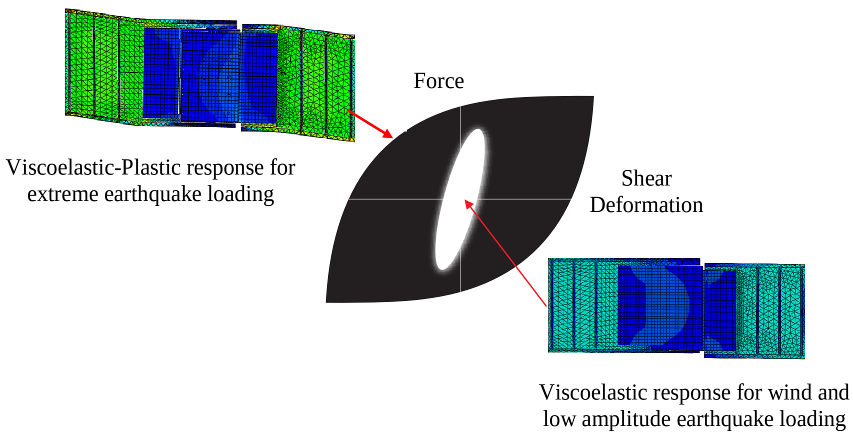


Figure 2. Outrigger VCD hysteretic response

MODELLING OF VISCOELASTIC COUPLING DAMPERS

In this paper, material properties for viscoelastic materials were determined using the Kelvin-Voight model as described by Christopoulos and Filiatrault [6]. The hysteretic restoring force F_{VE} provided by the viscoelastic panels is a function of the material elastic deformations and velocity:

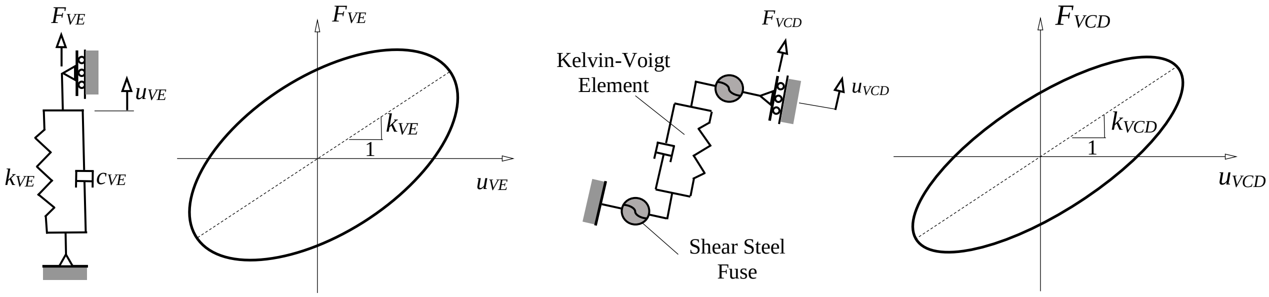
$$F_{VE} = k_{VE}u_{VE} + c_{VE}\dot{u}_{VE} \tag{1}$$

Where k_{VE} is the VE panels elastic stiffness, u_{VE} the induced shear deformations, c_{VE} the damping coefficient and $\dot{u}_{VE}$ the induced velocity. The stiffness and damping coefficients are a function of the material geometric properties, such as the area and thickness of the VE layers, as well as the rate of loading, and temperature self-heating effects. Viscoelastic materials transform mechanical input energy into heat. This energy dissipation mechanism modifies the material stiffness and damping properties, as the material raises the temperature at each VE layer. The Kelvin Voight model is a simple approach for VE materials, and a thorough study of macroscopic VE material models can be found in [20] (with application examples for VCDs).

The VCD mechanical behaviour can be modeled with a hysteretic spring in series with a Kelvin Voight element (Fig. 3(b)) [18, 21]. The VCD total deformation is a combination of the VE panel and shear link displacements, and it is represented as follows:

$$F_{VCD} = K_{VCD}u_{VCD} + C_{VCD}\dot{u}_{VD} \tag{2}$$

These constitutive models can be easily implemented in MATLAB scripts and in commercial structural analysis software such as ETABS and PERFORM 3D.



(a) (b)

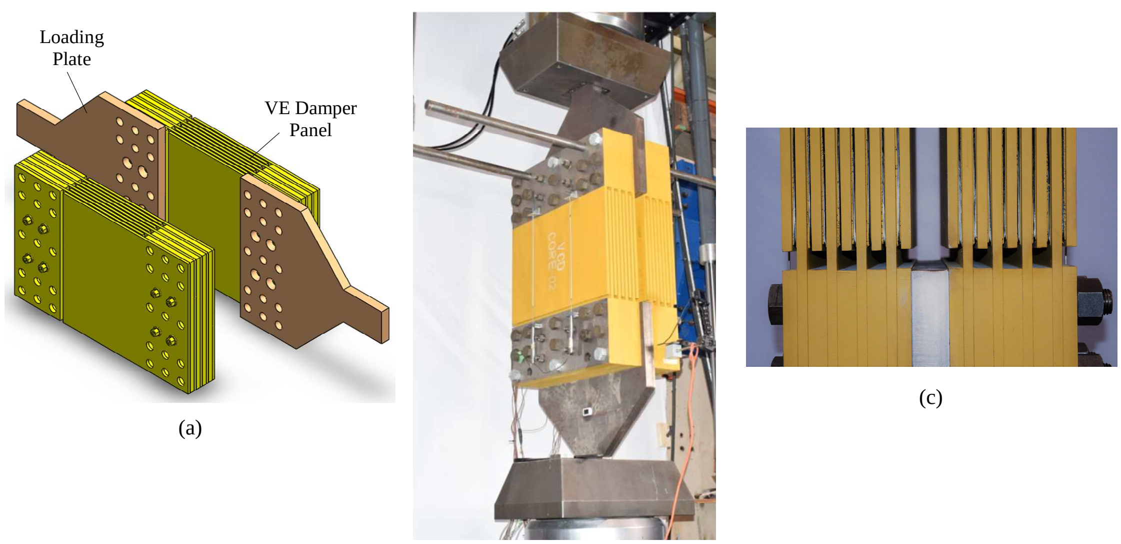
Figure 3. (a) Kelvin Voigt model for VE materials and hysteretic response, (b) Viscoelastic-plastic VCD model and viscoelastic hysteretic response

EXPERIMENTAL PROGRAM

The experimental program in this paper involves two full-scale testing setups. VE panels were tested in an axial configuration using the University of Toronto 2700 kN MTS machine, and more than 180 harmonic tests were conducted to characterize the material mechanical properties. A full-scale setup was designed to simulate the VCD boundary conditions in outrigger systems, and full-scale VCD specimens were fabricated by Nippon Steel Engineering Corporation (Tokyo, Japan).

VE panel testing setup

Two sets of viscoelastic panels (Panels A and B) were designed to provide adequate damping and stiffness to two proposed buildings. Preliminary material property tests performed in the first set of panels (Panels A) is subsequently presented in this chapter. Panels A consisted of eight VE layers (per panel) of 750 x 500 mm with 6.7 mm of thickness ISD111H material bonded to steel plates. The VE panels were bolted to two large loading stiff plates using a slip critical connection, and assembled in a MTS machine (Fig. 4). Four linear variable displacement transducers (LVDTs) were installed in the outer VE panel surfaces to measure material deformations. Type T thermocouples were embedded inside of the VE layers to measure the temperature raise at each viscoelastic hysteretic cycle. Displacement control loading protocols were applied by the MTS machine, and the corresponding loads were measured with its internal load cell. The minimum possible displacement applied by the test control was 1 μm.



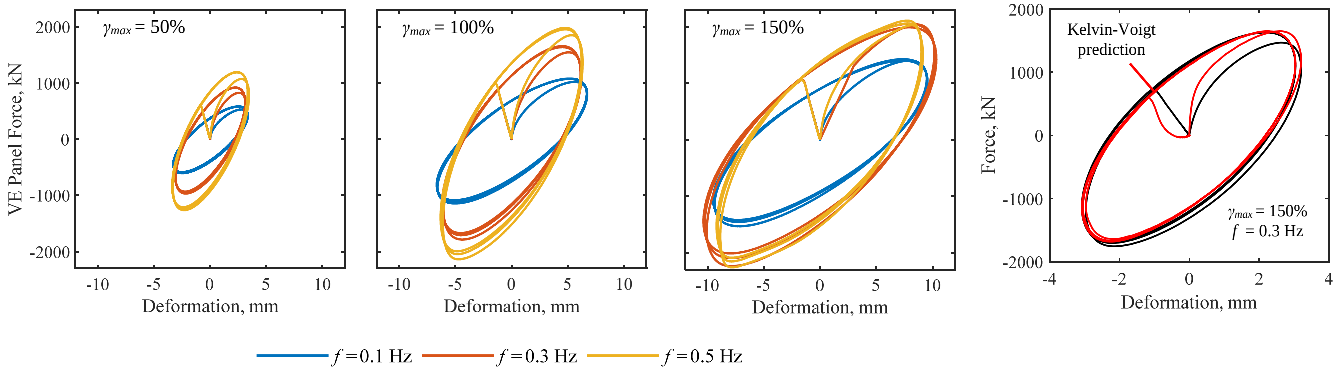
(a) (b) (c)

Figure 4. (a) VE panels testing assembly, (b) MTS experimental setup, (c) VE panels deformation for γ = 150%.

Harmonic loading protocols with three hysteretic cycles were applied to VE Panels A. An array of frequencies expected in the dynamic response of tall buildings were studied at three strain levels: γ = 50, 100 and 150%. Material properties using the Kelvin Voight model and Eq. (1) were calculated and are presented in Table 1; the summary of these harmonic tests is summarized in Fig. 5(a). Test results agreed with the stringent material testing procedures and properties reported by the damper manufacturer, 3M. Fig. 5(b)s a Kelvin-Voight prediction for γ = 150% and f = 0.3 Hz, demonstrating that this model (although simple) is effective to characterize VE materials.

Table 1. Summary of material properties for VE Panels A using the Kelvin Voigt model for γ = 50%

f (Hz)	k (kN/mm)	c (kNs/mm)
0.08	125.1	204.2
0.1	135.7	183.6
0.3	213.5	111.8
0.5	267.9	88.8



(a) (b)

Figure 5. (a) VE Panels A hysteretic response at various frequencies and strain amplitudes (b) Harmonic tests results at γ = 150% and f = 0.3 Hz and comparison with Kelvin-Voigt model.

Unlike solid damping systems which provide viscous damping at very small deformations (micron level), most hysteretic and viscous fluid dampers can only provide damping to structures at larger deformations. In order to evaluate the damping provided by VCDs at very small amplitudes of vibration (~5 μm), test protocols with a large array of testing strains: 0.05%, 0.1%, 0.2%, 0.3%, 0.5%, 1%, 2%, 5%, 10%, 20%, 30%, 50%, 100%, and 150%, at various frequencies: 0.05, 0.1, 0.15, 0.2, 0.3, and 0.5 Hz were conducted for Panel A. Tests results for the f = 0.3 Hz range are presented in Figure 6. The stable VCD hysteretic response and sustained damping at very small levels of excitation distinguish this damped outrigger system from most current damping technologies.

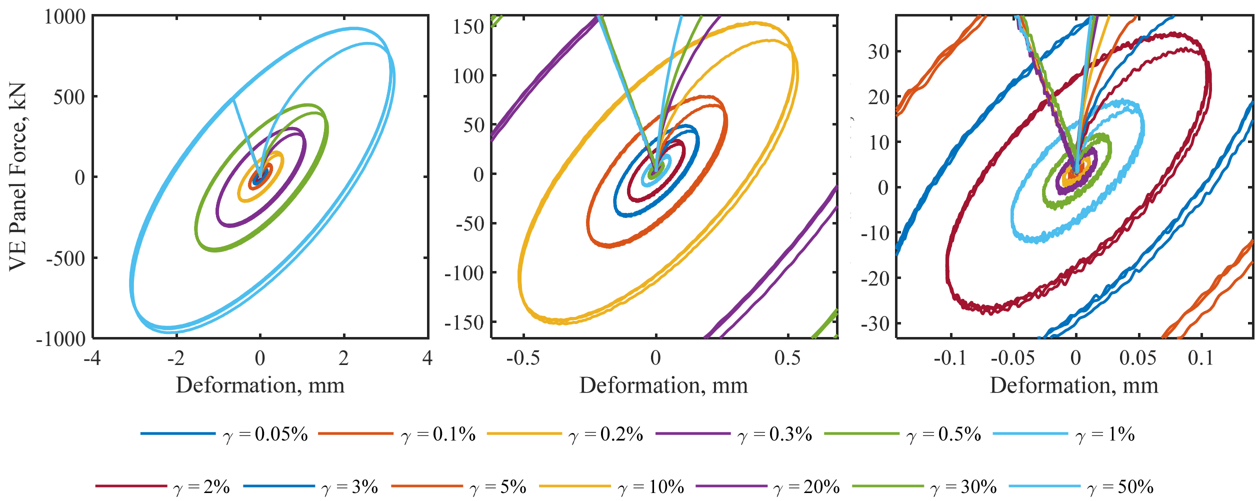


Figure 6. VE Panels A hysteretic response from small to large strains at f = 0.3 Hz.

4.2 Outrigger VCD full-scale testing

The testing setup consists of a full-scale outrigger VCD, with two shear link fuses and two-VE panels, connected to a base plate and anchored to a strong floor. The setup also includes two loading brackets supported by a rolling system, an out-of-plane support system, and three dynamic high-velocity actuators with their frame supports (Fig. 7a). Two different shear VCD end connection details were considered: an end plate replaceable connection (VCD-R) and a concrete wall embedded detail (VCD-E) as shown in Fig. 8. Eight full-scale specimens were designed. Four specimens used high performance, low yield point steel manufactured by Nippon Steel Engineering and were design for a 630 m tall building. The remaining four specimens used North American A992 steel and were designed for a 280 m tall building. All dampers have an ultimate strength capacity of approximately 4000 kN.

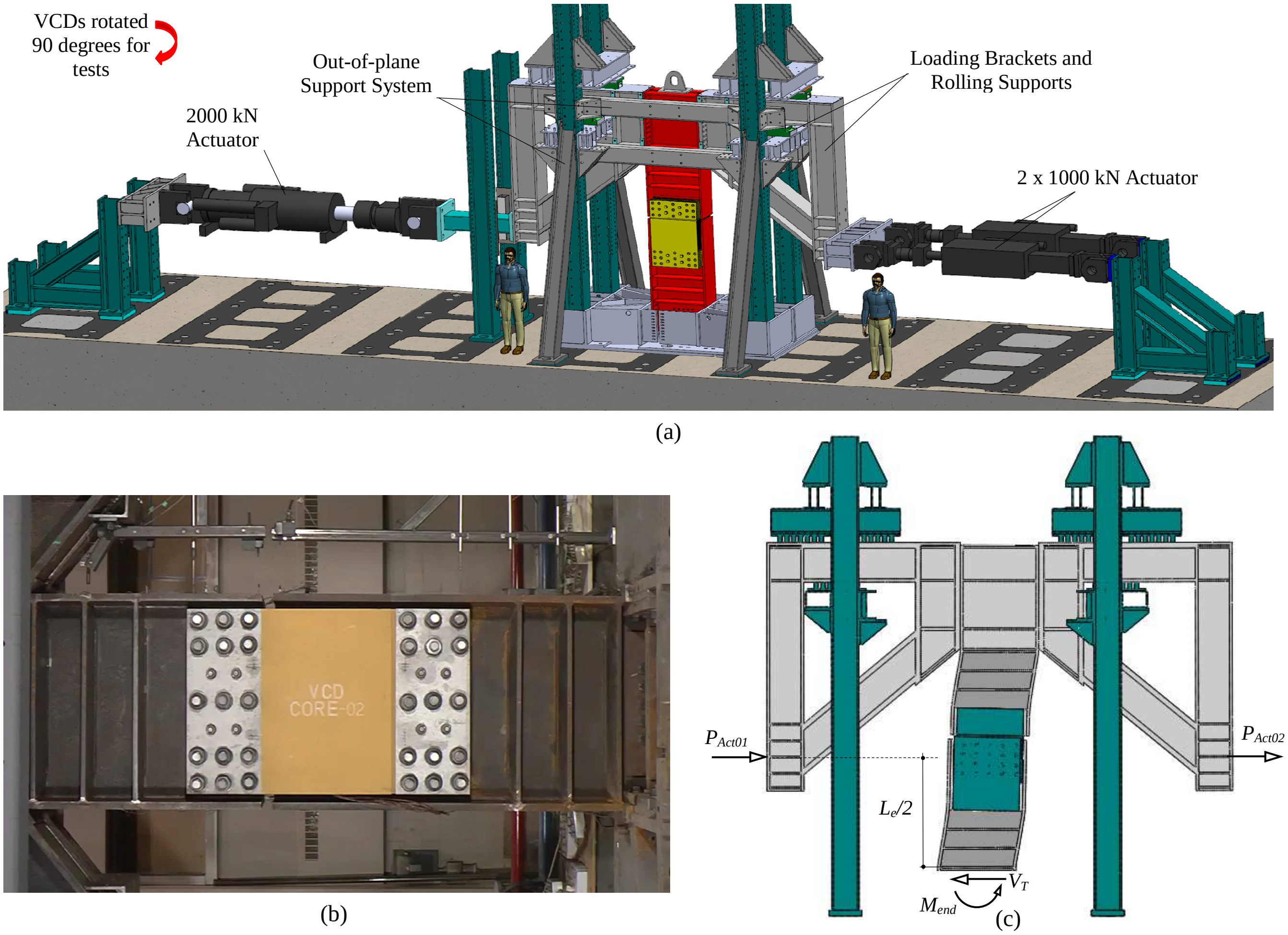


Figure 7. (a) Full scale testing setup (b) Close up rotated photo of VCD specimen (c) Free body diagram

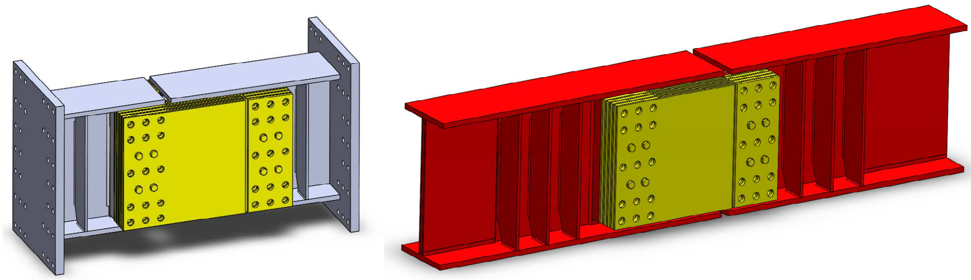
Outrigger VCDs were tested in double curvature with realistic boundary conditions simulating a real building application. Displacement control testing protocols were applied by synchronizing the three loading actuators. The displacement and load synchronization among the three dynamic actuators were confirmed by running a series of testing calibration protocols. Fig 7c. shows a deformed shaped for a push cycle imposed by the actuators, and a scheme to illustrate the transfer of loads from the actuators, though the testing apparatus into the specimen. The total shear load V_T, and end moments in the specimen can be calculated using equations 3 and 4 respectively.

$$V_T = P_{Act01} + P_{Act02} \quad (3)$$

$$M_{end} = \frac{V_T L_e}{2} \quad (4)$$

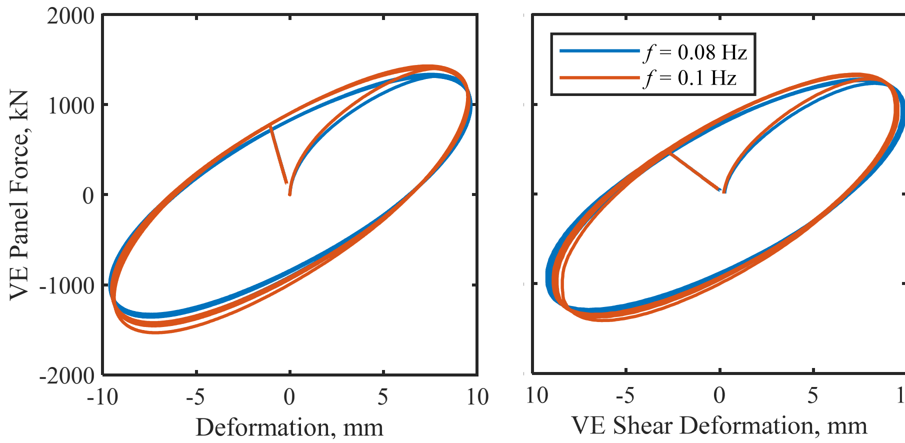
Strain rosettes and uniaxial strain gauges were placed in multiple locations of the specimen to identify changes of both strains and stresses, specially within the shear link fuses. Multiple LVDTs were located along the span of the specimen to capture the total VCD deformation. In addition, LVDTs were attached to the VE damper steel plates to measure the VE material deformation directly. The experimental setup was very densely instrumented with additional strain gauges, LVDTs and linear potentiometers to measure and track its overall structural behaviour and stability.

Preliminary harmonic testing protocols were applied to the specimen targeting the same strain levels achieved in the uniaxial tests presented in the previous section. Although the MTS tests imposed axial loads in the VE panels, each independent VE layer was strained in shear, and the shear deformations imposed in the full-scale setup are almost identical to the uniaxial test in both load and overall deformations. Fig. 9 shows a comparison between the VE panel response in the full-scale setup and the uniaxial MTS tests.



(a) (b)

Figure 8. Full-scale outrigger VCD specimens (a) replaceable end plate VCD-R (b) concrete wall embedded VCD-E



(a) (b)

Figure 9. (a) Harmonic hysteresis from MTS test at at $\gamma = 100\%$ and comparison (b) with Full scale shear set up.

A series of nonlinear response history analyses (RHAs) were performed for the sample building equipped with VCD-E, considering seven service level earthquake (SLE) ground motions, and windstorms with 1/1, 1/10, and 1/50 years return period. Three dimensional models of this megatall structure were built using Perform-3D [21]. The results from these analyses were used to prepare the corresponding testing protocols. For service level ground motions, the intended VCD response is predominantly viscoelastic, without any yielding of the steel connecting shear fuses. Figure 10 shows sample preliminary testing results with the corresponding hysteresis of the VCD, and VE panel; Fig. 10 confirms the intended viscoelastic VCD behaviour for SLE ground motions.

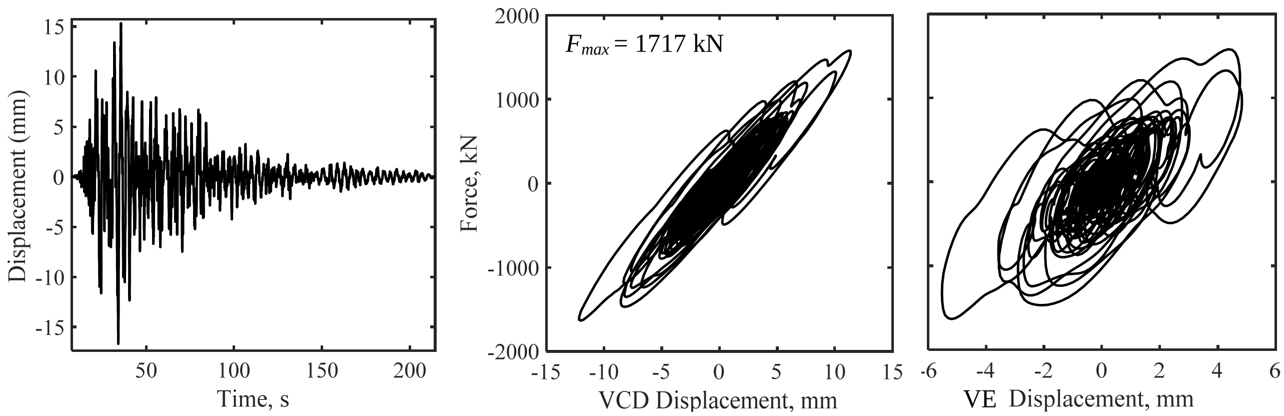


Figure 10. (a) Service level earthquake testing Protocol (b) VCD hysteresis (c) VE damper panel hysteresis

Wind testing protocols were prepared using the RHAs from the three-dimensional building model equipped with VCD-E subject to 12-hours windstorms. RHAs were carried out using windstorms provided by the wind tunnel consultant for the proposed building. Figure 11 shows the VCD hysteresis for one-hour peak of the 12 hours long duration ultimate-level (1/50 years) windstorm. Figure 11 confirms the intended behaviour of the outrigger VCD for design level windstorms.

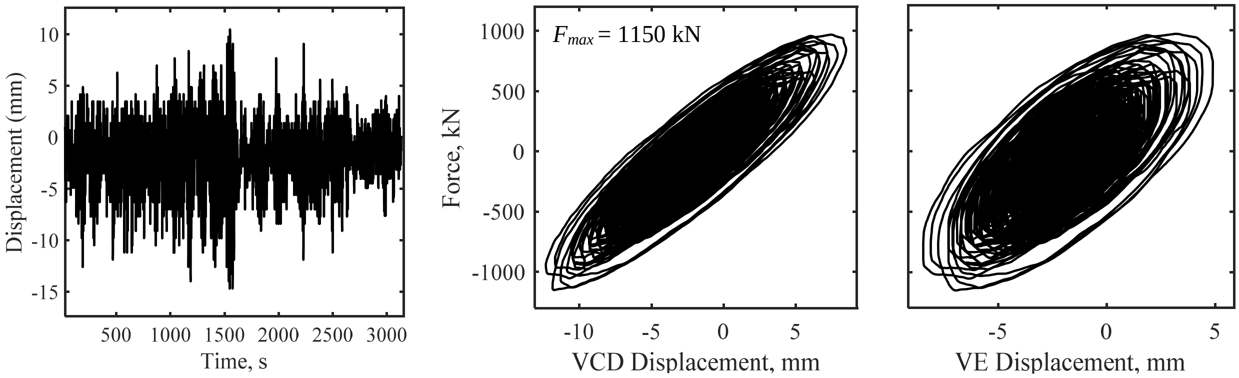


Figure 11. (a) Design level wind testing Protocol (b) VCD hysteresis (c) VE damper panel hysteresis

CONCLUSION

This paper presents experimental results of full scale VCD specimens designed to enhance the dynamic performance of two proposed buildings, both located in seismic zone areas. VCDs add distributed damping to all modes of vibration of tall buildings and provide multi-hazard protection while optimizing architectural sellable space. Simple numerical models for viscoelastic materials were discussed and compared to test results of VE damper panels and full scale VCDs. Experimental results validated the intended behaviour of these outrigger dampers for low amplitude vibrations, service level earthquake ground motions and ultimate level windstorms. A total of eight outrigger VCDs were introduced in this document, and an extensive experimental program is currently underway at the University of Toronto to validate the performance of this technology for tall buildings in outrigger systems.

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REFERENCES

[1] Los Angeles Tall Buildings Structural Design Council – LATBSDC (2017). *An Alternative Procedure for Seismic Analysis and Design of Tall Buildings Located in the Los Angeles Region*. Los Angeles, CA.
[2] International Code Council – ICC (2012). *International Building Code*. Country Club Hills, IL.
[3] Kareem, A., Kijewski, T., Tamura, Y. (1999). "Mitigation of motions of tall buildings with specific examples of recent applications". *Wind and Structures*, 2, 201-251.
[4] Moehle, J.P. (2006). "Seismic analysis, design, and review for tall buildings". *The Structural Design of Tall Buildings*, 15, 495-513.
[5] Smith, B.S. and Coull, A. (1991). *Tall building structures: Analysis and design*. John Wiley and Sons. New York, NY.
[6] Christopoulos C, Filiatrault A (2006). *Principles of Passive Supplemental Damping and Seismic Isolation*. IUSS Press: Pavia, IT.
[7] Sun Choi, H., Ho, G., Joseph, L., Mathias, N. (2012). *Outrigger Design for High-Rise Buildings*. Council of Tall Buildings and Urban Habitat. Chicago, IL.
[8] Viise, J., Ragan, P., Swanson, J. (2014). "BRB and FVD alternatives to conventional steel brace outriggers". In *CTBUH 2014 Shanghai Conference Proceedings*. Shanghai, China.
[9] Smith, R., Willford, M. (2007). "The damped outrigger concept for tall buildings". *The Structural Design of Tall and Special Buildings*,16, 501-507.
[10] Watanabe, A. (2018). "Design and applications of buckling-restrained braces". *International Journal of High-Rise Buildings*, 7-3, 215-221.
[11] Bashor, R., Bobby, S., Kijewski-Correa, T., Kareem, A. (2012). "Full-scale performance evaluation of tall buildings under wind". *Journal of Wind Engineering and Industrial Aerodynamics*, 104, 88-97.
[12] Kijewski-Correa. T. and Pirnia, D. (2007). "Dynamic behaviour of tall buildings under wind: Insights from full-Scale monitoring". *The Structural Design of Tall and Special Buildings*, 16(4), 471-486.
[13] Satake, N., Suda, K., Arawaka, T., Sasaki, A. and Tamura, Y. (2003). "Damping evaluation using full-scale data of buildings in Japan". *ASCE Journal of Structural Engineering*, 129(4), 470-477.

[14] Couture, B. (2019). Full-Scale Monitoring of a Tall Slender Building with Viscoelastic Coupling Dampers. MASc. Thesis., University of Toronto, Toronto, ON.

[15] Christopoulos., C., Montgomery., M. (2013). “Viscoelastic coupling dampers (VCDs) for enhanced wind and seismic performance of high-rise buildings”. *Earthquake Engineering and Structural Dynamics*, 42, 2217-33.

[16] Montgomery. M., Christopoulos. C. (2014). “Experimental validation of viscoelastic coupling dampers for enhanced dynamic performance of high-rise buildings”. *ASCE Journal of Structural Engineering*, 141, 04014145.

[17] MacKay-Lyons. R., Christopoulos., C., Montgomery., M. (2019). “Viscoelastic coupling dampers (VCDs) for enhanced multiple seismic hazard level performance of high-rise buildings”. *Earthquake Spectra.* In press.

[18] Montgomery M., (2011). “Fork configuration dampers (FCDs) for enhanced dynamic performance of high-rise buildings”. PhD Dissertation, University of Toronto, Canada.

[19] Pant, D., Montgomery, M, Christopoulos, C., Xu, B., Poon, D. (2017). “Viscoelastic coupling dampers for the enhanced seismic resilience of a megatall building”. *16th World Conference on Earthquake Engineerin*g. Santiago, Chile: International Association for Earthquake Engineering.

[20] Pant, D., Montgomery, M., Christopoulos, C. (2019). “Full-scale testing of a Viscoelastic Coupling Damper for High-Rise Building Applications and Comparative Evaluation of Different Numerical Models”. *ASCE Journal of Structural Engineering*, 145(2), 04018242.

[21] Kasai, K., Minato, N., and Kawanabe, Y. (2006) “Passive control design method based on tuning equivalent stiffness of visco-elastic damper”. *Journal of Construction Engineering, AIJ*, 610(12), 75-83.

[22] PERFORM-3D. (2013) Nonlinear Analysis and Performance Assessment of 3D Structures, Computer Program, Computers and Structures Inc., Berkeley, CA, USA.