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Enhancing seismic performance of buildings using viscous wall dampers

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ABSTRACT

Energy dissipation devices are effective solutions for enhancing the seismic performance of buildings through reducing the dynamic and seismic demands, especially interstory drifts. Viscous wall dampers (VWDs), especially designed to behave as passive energy dissipation devices, are being extensively used in Japan to improve structural performance by reducing seismically induced structural damage. VWDs have been used mainly in flexible framing systems, such as moment frames, to reduce interstory drifts and inelastic behavior in beams and columns. So far, the VWD system has been used in more than 100 projects in Japan, one project in USA, and one in Mexico. This paper describes the VWD devices, shows the results of full-scale prototype testing, summarizes VWD properties, and explains modeling techniques for use in nonlinear history analysis. This paper also presents some case studies from Japan, where the VWDs were originally developed, USA and Mexico. These case studies include both new and retrofit projects.

1 INTRODUCTION

Earthquakes cause severe causalities around the world every year. Conventional seismic design methods usually focus on designing the buildings with ductility where the building will be damaged in a strong seismic event but won't fail. Collapse is avoided by absorbing the earthquake energy through plastic deformation of yielded members. To avoid the buildings being damaged and to keep them functional after an earthquake, engineers and researchers have turned to different alternatives. Energy dissipation devices such as viscous linear dampers and viscous wall dampers (VWDs) are effective solutions for improving the seismic performance of buildings. These damping devices are used to reduce the seismic demands on the structure, and hence reduce the damage during an earthquake.

The objective of this paper is to describe the VWD devices, present their applications around the world, show test results and properties, and explain practical modelling techniques to be used in nonlinear time history analysis.

2 VISCOUS WALL DAMPERS (VWD)

VWDs were developed in Japan in the late 1980s by engineers at Sumitomo Construction Company, Ltd. (Arima et al. 1988). VWD's are passive energy dissipation devices that reduce seismic accelerations, interstory drifts and wind-induced vibration. They are effective and easier to implement compared to active and semi-active systems.

A schematic presenting the main components of a typical VWD is shown in Figure 1. A VWD consists of a narrow steel tank connected to the lower floor, an inner steel plate (vane) connected to the upper floor, and viscous fluid in the gap in between. During seismic events or wind excitations, the relative floor movement causes the vane to move through the viscous fluid. Viscous shearing of the fluid relative to the vane and tank wall provides damping and energy dissipation. VWDs can also be manufactured with two vanes where the tank is modified and formed of three plates. Double-vane VWDs can provide twice the damping force with only a small increase in thickness compared to a single-vane wall damper. VWDs do not operate under pressure and do not have seals that require maintenance throughout the life of the device. Besides inspection after a seismic event and periodic inspection, the VWD system is maintenance-free.

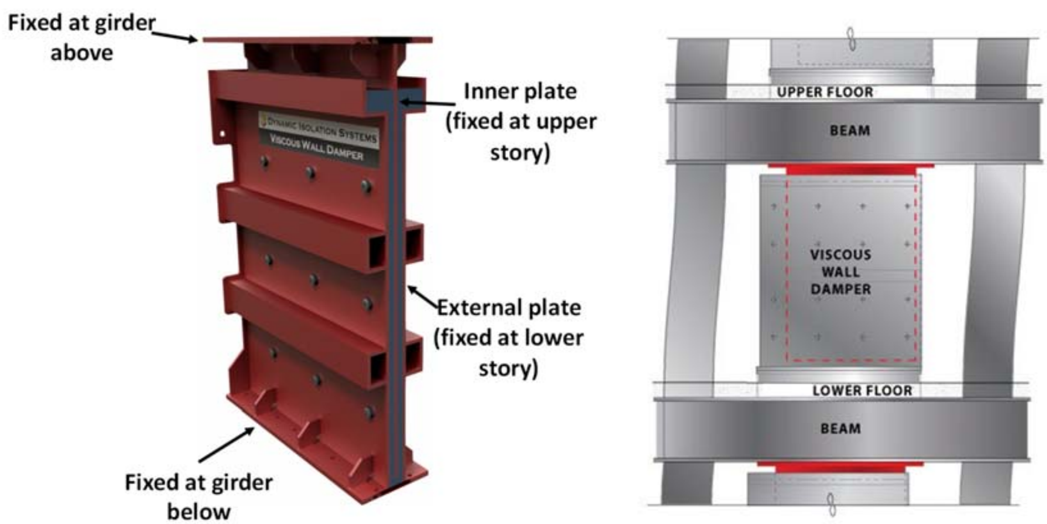


Figure 1: Schematic representation of single-vane VWD and typical framing elevation

The viscous fluid used for VWDs is a non-toxic, odourless, transparent fluid with a viscosity of 90,000 poise at 30^{o} C. Customized sizes of VWDs can be manufactured to fit different openings in a building. Dampers with heights of 6 ft to 14 ft and widths of 6 ft to 20 ft have been used. Smaller dimensions are used for overseas freight; 12 ft maximum height and 8 ft maximum width. Recently, VWDs were introduced to the US market by Dynamic Isolation Systems, Inc. (Newell et al. 2011). The following section presents examples of previous VWD projects in different countries.

3 PREVIOUS VWD PROJECTS

3.1 Japan

There has been more than 100 VWD projects in Japan and some selected projects are briefly discussed in this section. The SUT-building was constructed in Shizouka city using a total of 170 VWDs that were installed in the steel frame building during 1992/1993 (Miyazaki and Mitusaka 1992). The target value for the damping was 20% to 30% in the elastic range of the frame. The main objective was to keep all the maximum responses in the elastic range of the frame without any damage against maximum credible earthquakes.

Because of the VWDs, the seismic demands were reduced by up to 70% and the no-damage objective was achieved. The SUT building is considered the world's first building with such a large energy absorbing capacity.

VWDs were also used in the Kanto postal office building (Fig. 2a) which was constructed in Omiya (Kihara et al. 1998). This office is the local administrative authority for the Ministry of Posts and Telecommunications in Kanto and Tokyo area and considered the base to take measures against earthquake disasters. More than 400 VWDs were used in this 28-story building. Story drifts were reduced by about 50% to 67% in an MCE event. Wind accelerations were also reduced to about 1/3. Figure 2b shows Waseda University building in Tokyo during construction where the VWD system was used to enhance the seismic performance of the building and minimize the seismic demands from earthquakes.

(a)

(b)

Figure 2: Selected VWD projects in Japan. a) Kanto postal office building and b) Waseda University

3.2 United States

The new California Pacific Medical Center (CPMC) is the first project in the US to use VWDs (Newell et al. 2011 and Love et al. 2012). It is located in San Francisco, CA, only 11 km from the San Andreas fault. Hospitals are critical facilities to post-disaster response and being operational after a seismic event. The concern is not only the structural seismic performance but also the performance of the non-structural elements. The damage to non-structural components can put a hospital out of service until repairs are made. This damage is very sensitive to floor accelerations. The decision was made to use the VWD technology to help achieve the structural and non-structural performance goals.

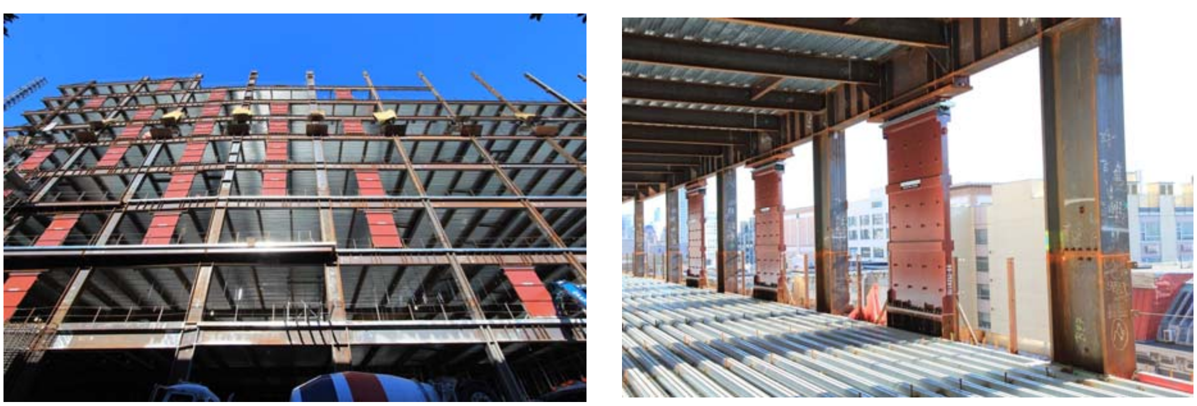


Figure 3: Construction of the new California Pacific Medical Center

The hospital was originally designed to be 15 stories, but the final design came as 12 stories and two parking levels. The main lateral force resisting system is a steel moment resisting frame with 119 VWDs to provide the supplemental damping. The preliminary design included three systems; a conventional welded steel moment resisting system, a base-isolated system with steel braced frame, and steel moment resisting frame with supplemental damping. The damped steel moment resisting frame system was selected as it provided significant savings in steel material compared to the other two systems. With the cost of dampers compared against the cost of additional steel, use of VWDs ended up saving about 25% of the total cost of structural steel for the project. Furthermore, the system with VWDs was simple and preferred over the moat system accompanied with the base isolation option. In addition, the VWDs could be located between the windows on the exterior façade, providing light access in the patient rooms which would be less with the braced-frame solution. Figure 3 shows the field installation of VWDs and construction of the new hospital.

3.3 Mexico

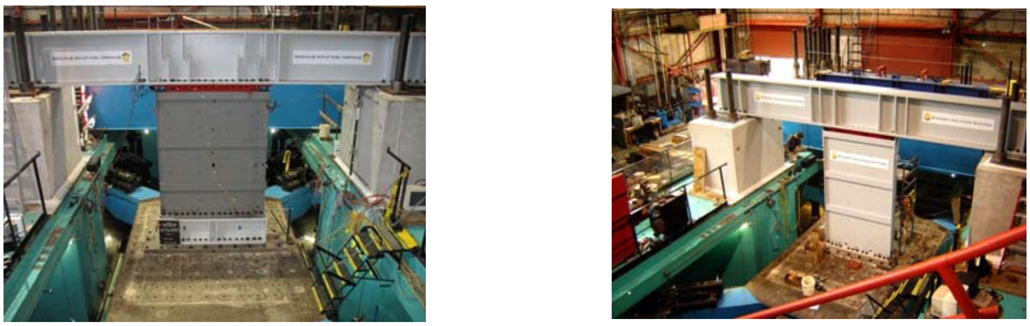
The Harbour 171 project, shown in Figure 4, is the first project in Mexico to use VWDs. It consists of two existing buildings which are being retrofitted into luxury ocean-front condominiums. Each building has 14 floors, consisting of 13 levels of apartments and a 14th level of penthouses. The development is located waterfront on the Playa Camarones in Puerta Vallarta and is within walking distance of the Malecon boardwalk. The buildings were constructed in the 1990's but were not used due to financial reasons. In 2016, the owners decided to occupy the buildings, however, the seismic hazard in this region increased since the 1990's. The owner, the architect and the structural engineer decided to use VWDs to retrofit the buildings and reduce the seismic demands to meet the code limits.

Figure 4: The Harbour 171 project in Mexico and VWD installation

4 FULL-SCALE TESTING

As part of the CPMC project in the US, full-scale testing was conducted on the VWDs. VWDs are both displacement- and velocity-dependent and the objective of the tests was to establish expected seismic and wind performance and to determine appropriate properties used for modeling the dampers.

Prototype tests on two damper sizes, 7 ft × 9 ft and 7 ft × 12 ft, were performed at the University of California, San Diego (UCSD) at Caltrans Seismic Response Modification Device Test Facility as shown in Figures 5a, b. The double-vane dampers were tested to different displacements and velocities using both sinusoidal and earthquake motions in single and bi-directional loading conditions. The parameters that define the performance of the dampers are shown in Figure 6a. Figures 6b and 6c show typical force-displacement response for cyclic and earthquake tests. The earthquake test is for a ground motion representing the Maximum Considered Earthquake (MCE) for the site. The MCE is defined as the lesser spectrum of the probabilistic seismic hazard analysis for the 2% probability of exceedance in 50 years, or the 84% percentile of the deterministic earthquake from the governing fault (Love et al. 2012). A wind tunnel test on a building model was used to determine the building response during a 100-year wind event. The data from the wind tunnel test was used to develop wind test loading sequence for the wall dampers where a static displacement was applied first and then simultaneous combination of quasi-static and dynamic cycles were then applied (Fig. 7a). Five tests of 1000 dynamic wind load cycles were conducted without significant change in damper properties. Figure 7b shows the force-displacement response for one typical quasi-static cycle and superimposed dynamic cycles of the wind test. VWDs provided significant levels of damping even for small wind displacements.



(a) (b)

Figure 5: VWD full-scale testing: a) 7 ft × 9 ft specimen, b) 7 ft × 12 ft specimen

5 VWD PROPERTIES AND MODELING PARAMETERS

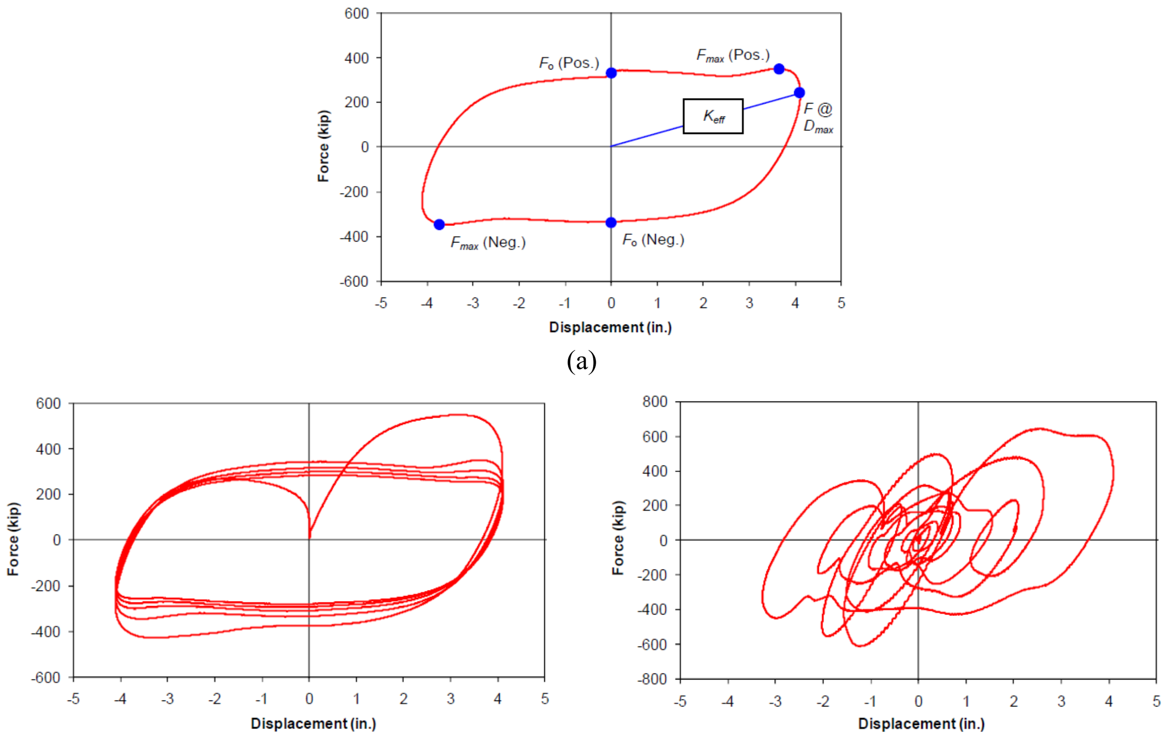
Based on the results of CPMC prototype testing, VWD properties and modeling parameters were developed for implementation in nonlinear time history analyses. The seismic response of the wall dampers can be readily modeled using existing nonlinear elements in SAP2000, ETABS or PERFORM 3D. VWDs are best represented by an Exponential Maxwell Damper Model schematically shown in Figure 8. The model consists of a linear spring, K, in series with an exponential damper characterized by C and α. A nonlinear Maxwell model was used in SAP2000 to fit the prototype test results for the two tested wall dampers. Selected force-displacement comparisons between the prototype test results and the analytical model are shown in Figure 9. The recommended nominal properties for the VWDs at 70ºF are presented in Table 1. More information can be found in the viscous wall damper modelling guide (Dynamic Isolation Systems, 2016)

Table 1: Nonlinear nominal properties for VWDs used in the CPMC project

VWD Size	K (kip/in)	C [kip-(sec/in)$^{\alpha}$]	A (dimensionless)
7 ft × 9 ft	410	108	0.5
7 ft × 12 ft	450	150	0.5

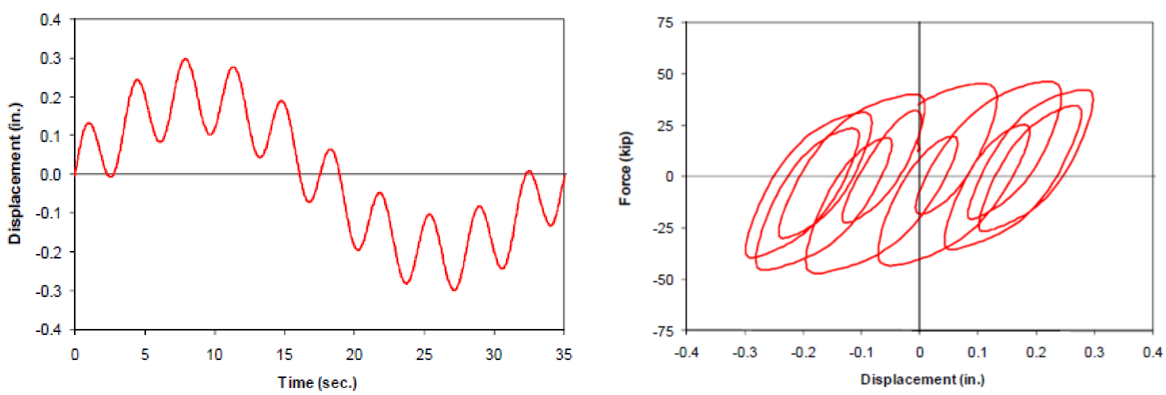
5.1 VWD property modification factors

In accordance with the requirements of Chapter 18 of ASCE7-16, seismic analysis is typically performed with maximum and minimum properties for the VWDs. These properties are derived from the nominal properties through use of property modification factors which take into account the first-cycle effect, temperature variation, aging and specification tolerance. Table 2 provides a summary of upper and lower bound property modification factors. As observed in Figure 9a, VWDs typically exhibit a higher force in the first cycle which is not captured by the analytical model. A first-cycle effect upper bound property modification factor is used to ensure the building is properly designed for the increased force demand. The temperature and aging factors shown in Table 2 were established based on Japanese experience with previous projects while the specification tolerance factors are based on ASCE7-16 requirements.



(b) (c)

Figure 6: Force-displacement response for VWD: a) VWD property definition, b) Sample cyclic test with a maximum velocity of 5.1 in/sec and maximum displacement of 4 inches, c) Simulated earthquake test using a scaled ground motion to match the MCE response spectrum for the site



(a) (b)

Figure 7: a) Typical quasi-static cycle with the superimposed dynamic cycles of wind test sequence and b) Typical force-displacement response for wind test. The static displacement offset has been removed from the plots

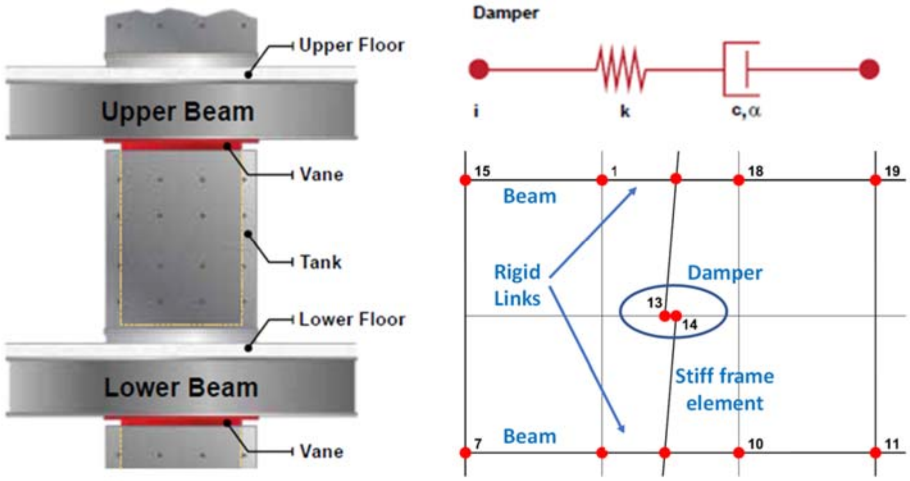
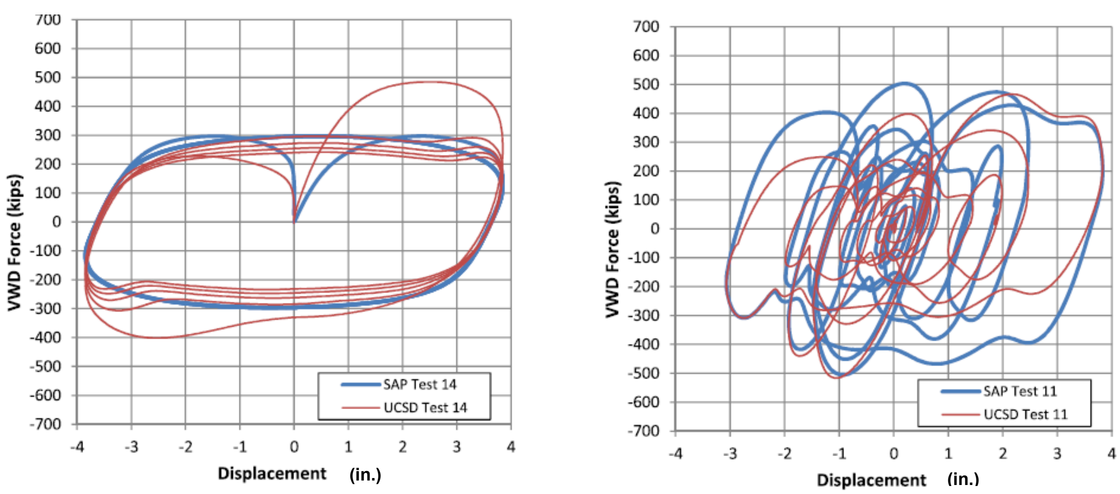


Figure 8: Schematic representation of VWD modeling technique for nonlinear analysis

Table 2: Property modification factors for VWDs

Source of variation	Upper bound property multiplier (λmax)	Lower bound property multiplier (λmin)
First cycle effect (testing), λ_{test}	1.55	1.00
Aging and environment, λ_{ae}	1.08	0.89
Specification tolerance, $\lambda_{spec,a}$ (all dampers)	1.10	0.90
Specification tolerance, $\lambda_{spec,i}$ (individual dampers)	1.15	0.85



(a) (b)

Figure 9: Force-displacement comparisons between UCSD test results and the analytical model for the 7ft × 9ft VWD: a) Cyclic test with nominal properties and maximum velocity of 7.6 in/sec and b) Simulated earthquake test with λ_{test}=1.55 and maximum velocity of 11.3 in/sec

6 SUMMARY AND CONCLUSIONS

Viscous wall dampers (VWDs) are passive damping devices that are used for seismic protection of new buildings and seismic retrofitting of existing structures. VWDs have been used mainly in flexible framing systems such as moment frames to reduce interstory drifts and inelastic behavior in beams and columns. VWDs also reduce the floor accelerations and accordingly improves the seismic performance of the non-structural components and protect the building contents. The VWD system has been used extensively in Japan since the 1990s. So far, there have been more than 100 wall damper projects in Japan, however, there are few projects in other countries. The California Pacific Medical Center (CPMC) is the first VWD project in the US. VWDs can be used to ensure continuous operation of the hospitals after a strong seismic event. Full-scale testing was conducted on VWDs to establish the expected seismic and wind performance and to confirm the properties used for modeling the dampers. VWDs can generate significant levels of damping during frequent and rare earthquakes and even with small wind-induced displacements. Upper and lower bound property modification factors should be considered when analyzing a VWD system in order to appropriately capture the expected range of a building response. The authors foresee the VWDs being used in more hospitals and see strong interest for retrofitting buildings that will benefit from reduction in seismic demands, especially for pre-Northridge steel moment frames with limited ductility.

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