SEISMIC PERFORMANCE OF TUNED VISCOUS MASS DAMPER (TVMD) COUPLED WALL SYSTEM FOR HIGH-RISE BUILDINGS

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Abstract

A new tuned viscous mass damper (TVMD) coupled wall system is proposed for use in high-rise buildings. This system is expected to suppress both of inter-story drifts and floor accelerations for protecting structural and non-structural components in an earthquake event. The TVMD consists of a component that provides stiffness, connected in series with a ball screw device that offers large inertial and damping forces even under small deformations. In this novel system, TVMDs are arranged to connect adjacent wall piers in a zig-zag configuration. Such a strategic arrangement of TVMDs makes efficient use of the vertical relative displacements of the adjacent walls induced by their flexural deformation to generate the motions and forces of the TVMDs. A method based on fixed-point theory has been developed for the optimal design of this system. In this method, the inertial masses of TVMDs distributed along the structural height are assigned to be proportional to their corresponding modal displacement demand, and the frequency of all TVMDs is tuned to a single vibration mode of the primary structure. In this study, the finite element analysis of a 15-story prototype structure is conducted to investigate the seismic performance of the new structural system. To simulate the dynamic behavior of TVMDs, a new element is compiled in the computational platform OpenSees. The accuracy of the TVMD model is validated against experimental data. The shear walls are simulated using the multi-layer shell elements. Nonlinear time history analysis is conducted on the TVMD coupled wall system (TCW). The other two cases are considered for comparison, one using viscous damper coupled walls (named as VCW) and another using RC beam coupled walls (named as RCW). Seven ground motion records are selected as the input excitations, and four seismic intensities are considered.

Analysis results indicate that when the mass ratio is set to be 0.1 and the TVMDs are tuning designed to the second mode of the primary structure, the peak inter-story drifts of the TCW system are up to 8% and 16% smaller than those of the VCW and RCW system. The maximum peak floor accelerations of the TCW system are up to 15% and 28% smaller than those of the VCW and RCW system. The vibration control mechanism of the TCW system is interpreted based on the nonlinear analysis results. The vibration control mechanism of inter-story drifts is associated with the energy dissipation of TVMDs, whereas the control of floor accelerations is attributed to significantly suppressing the second mode vibration by the tuning effect.

Keywords: tuned viscous mass damper; coupled wall system; nonlinear time history analysis; seismic response control

1. Introduction

Control of both inter-story drifts and floor accelerations is necessary for enhancing the seismic resilience of high-rise buildings. Reinforced concrete (RC) shear walls are commonly used as the lateral resisting system of high-rise buildings. Due to their high lateral stiffness, RC wall systems can adequately control the inter-story drifts of buildings, but often amplify the floor accelerations at the same time. Because of the small inter-story drift and flexural-dominated lateral deformation mode, the installation of traditional dampers cannot efficiently provide sufficient additional damping to the RC wall systems and suppress the acceleration response. To overcome this difficulty, a new structural system named tuned viscous mass damper (TVMD) coupled wall system (see Fig. 1) is proposed to enable control of both the inter-story drifts and floor accelerations of high-rise buildings [1].

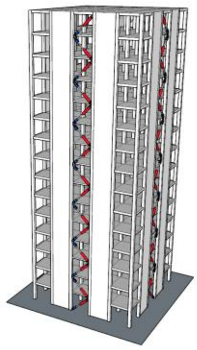
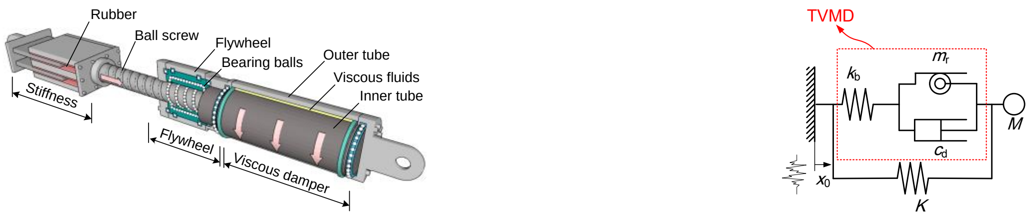


Fig. 1 – Schematic drawing of TVMD coupled wall system

In this system, a new kind of energy absorbers named tuned viscous mass damper (TVMD) is installed in the coupled wall system. The TVMD (see Fig. 2 (a)) consists of a viscous mass damper (VMD) [2] and a spring that connects the VMD to the structure [3]. The VMD is formed based on a ball screw system by connecting a rotational inertial mass in parallel with a rotational viscous damper. The inertial mass (m_r in Fig. 2 (b)) mentioned here shares the same idea of inerter [4]. When a TVMD is used in a structural system, the additional TVMD vibration system is designed to have a fundamental period close to that of the primary system and substantial energy dissipation can be achieved by amplifying the displacement of the damper in the TVMD. In the TVMD coupled wall system, TVMDs are arranged between two adjacent wall piers in a zig-zag configuration. The previous study has shown such a strategic arrangement of TVMDs makes efficient use of the vertical relative displacements to generate the motions and forces of the TVMDs [1].



(a) Schematic of TVMD (b) Mechanical model of the TVMD-SDOF system

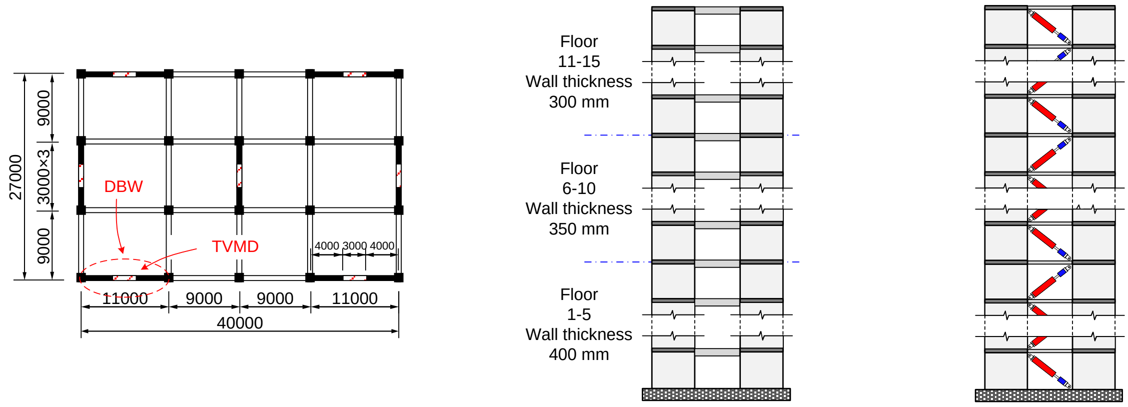
Fig. 2 – Tuned viscous mass damper

The objective of this study is to assess the seismic performance of the TVMD coupled wall system, especially when the RC wall piers undergo yielding and develop nonlinearity. To that end, a finite element (FE) model of the TCW system in a 15-story high-rise building was developed by the opensource finite element analysis software OpenSees, in which a new element named InertiaTruss was coded and compiled to simulate the behavior of inerter and form the model of the TVMD. The second section describes the structural design of the prototype structure and the TCW system. The third section describes the development of the TCW FE model. The fourth section summarizes the nonlinear time-history responses of the TCW, VCW, and RCW system and demonstrates the vibration control mechanisms.

2. Prototype structure and design of the TCW system

2.1 Prototype structure

A 15-story building adopting the RC frame-shear wall system is designed for analysis in this study. The building is assumed to be located in Beijing, where the peak ground acceleration (PGA) is 0.2 g for the design basis earthquake (DBE, with a probability of exceedance of 10% in 50 years) and the characteristic site period T_g is 0.45 s. The floor plan is shown in Fig. 3 (a). The total height of the structure is 67.5 m with a uniform story height of 4.5 m. The structure is designed following Chinese code for seismic design of buildings (GB 50011-2010) [5] and Chinese technical specification for concrete structures of tall buildings (JGJ 3-2010) [6]. A damping ratio of 5% is assumed for the primary structure. The wall thickness varies from 400 mm to 300 mm for different stories (see Fig. 3 (b)). The Chinese code [5] limits the inter-story drift ratio to 1/800 for RC frame-wall structures under the service level earthquake (SLE, with a probability of exceedance of 63% in 50 years and a peak ground acceleration of 0.07 g). This strict drift limit results in the design of relatively stiff buildings. The fundamental frequency of the designed prototype structure is 1.57 s if using RC coupling beams. In this study, the highlighted coupled wall is selected for analysis.



(a) Plain view of prototype structure (mm) (b) Elevation of the RCW (c) Elevation of the TCW

Fig. 3 – Prototype structure

2.2 Design of the RC beam coupled wall

The RC coupled wall system is named the RCW system for simplicity in this study. Fig. 4 shows the dimensions and reinforcement layouts. The RCW system is designed to have a coupling ratio of 38.2% following El-Tawil and Kuenzli's recommendation [7]. The two boundary columns of prototype walls are ignored for simplicity of analysis, which does not affect the comparison of various wall systems. C45 concrete (nominal cubic compressive strength $f_{cu,n}$ = 45 MPa and nominal axial compressive strength f_{ck} = 29.6 MPa) and HRB400 rebars (nominal yield strength f_y = 400 MPa) are adopted for the wall piers. The boundary elements and reinforcements are designed to satisfy the strength demand under SLE and the requirement of reinforcement details per GB 50011-2010 provisions [5].

The conventional RC coupling beams are adopted in the RCW as in usual Chinese structural designs. The sectional widths of the RC coupling beams are identical with the wall pier thickness. The beams are designed to be governed by flexure to ensure adequate ductility and satisfy the "strong shear and weak bending mechanism" according to Chinese code GB 50011-2010 [5] recommendation. The floor seismic mass acting on the RCW varies from 50 ton to 63 ton for different stories as listed in Table 1.

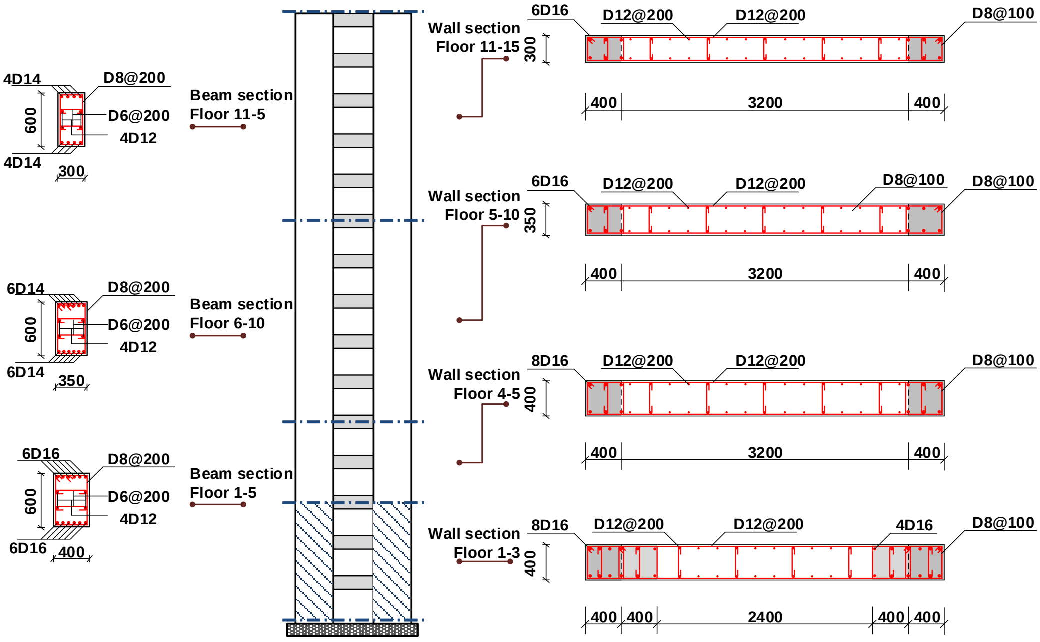


Fig. 4 – Wall dimensions and reinforcement details (unit: mm)

Table 1 – Seismic mass loaded on the coupled wall system

Story	1	2	3	4	5	6	7	8
Seismic mass (ton)	60.0	60.0	60.0	60.0	60.0	54.4	54.4	54.4
Story	9	10	11	12	13	14	15	
Seismic mass (ton)	54.4	54.4	54.4	50.4	50.4	50.4	63.2	

2.3 Design of TVMDs

Based on this prototype structure, the TVMD coupled wall can be formed by installing TVMDs between two adjacent wall piers as shown in Fig. 3 (c). As the installation of the TVMD increases the damping ratio of the structure, the stiffness demand of the coupling beam is decreased in the TCW system and thus the section height of the coupling beam can be reduced. The primary coupled wall system with reduced beams is named PCW. With the dynamic properties of the PCW, TVMDs can be designed by the single-mode tuning design method as presented in the previous study [1]. In this method, all TVMDs are tuning designed to a single tuning mode and the apparent masses are assumed to be proportional to the modal displacement demand vector of TVMDs along the height of the structure. For a given mode, the modal displacement demand of a TVMD is defined as the relative displacement between the two nodes where TVMDs will be installed. With a given mass ratio and tuning mode, the optimal frequency ratio and damping ratio of TVMDs can be calculated by Ikago et al.'s [3] optimal design equations for the SDOF system.

In this case, the mass ratio is set to be 0.1, and the TVMDs are tuned to the 2nd mode of the PCW to suppress both of inter-story drifts and floor accelerations [1]. Note that, the addition of the TVMDs can not only suppress the dynamic response of the tuning mode (i.e., the 2nd mode) but also provide additional damping to the lower-order mode (i.e., the 1st mode), due to the inherent characteristic of TVMDs [1]. The design inner forces of structural components and inter-story drifts of the TCW system are calculated using the linear response spectra analysis under SLE in accordance with the Chinese design code. With the distributed TVMD dampers along the height, the system shows non-classical damping characteristics, and thus the complex complete quadratic combination (CCQC) method [8] is used for modal response combination. The iteration design determines the parameters of RC coupling beams, as listed in Table 2. The optimal design results of the TVMDs are summarized in Table 3. The total apparent mass of the TVMDs is 369 ton.

Table 2. Design parameters of RC coupling beams in the TCW system

Story	*b* (mm)	*h* (mm)	Longitudinal reinforcement (mm)	Hoops (mm)
1 to 5	400	500	6D14	D8@100
6 to 10	350	500	4D16+2D14	D8@100
11 to 15	300	500	4D14	D8@100

Notes: *b* and *h* denote width and depth of the section, respectively; the top and bottom longitudinal rebars in the coupling beams are symmetrical, and this table presents the rebars in either side.

Table 3. Tuning design results of TVMDs

Story	m_r (ton)	k_b (kN/m)	c_d (kNs/m)	Story	m_r (ton)	k_b (kN/m)	c_d (kNs/m)	Story	m_r (ton)	k_b (kN/m)	c_d (kNs/m)
1	8	2539	58	6	18	5408	124	11	30	9142	210
2	20	6043	139	7	9	2780	64	12	38	11410	262
3	26	7790	179	8	1	260	6	13	43	12877	295
4	27	8077	185	9	11	3411	78	14	45	13584	312
5	24	7235	166	10	21	6388	147	15	46	13715	315

3. Finite element model

3.1 FE model of TVMD

As commonly used FE software does not provide an element or a model for TVMD, a novel model is developed to represent the TVMDs in the opensource FE analysis platform OpenSees. A TVMD model can be separated into 3 elements – a viscous damper, an inerter and a spring (shown in Fig. 5). For vicious dampers and springs, there have been kinds of mature elements for use, therefore the key problem is the modeling of inerter. To solve this problem, the authors develop a new element named InertiaTruss to simulate the behavior of inerter and form the TVMD model in OpenSees.

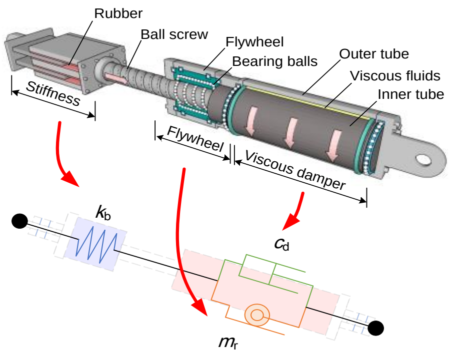


Fig. 5 – Finite element model of TVMD

A TVMD or an inerter can only generate or transmit axial force. It is a natural choice to develop this inerter element based on a 3D truss element. As shown in Fig. 6, like the Truss class, the InertiaTruss class also inherits from the Element class. In the InertiaTruss class, the mass matrix that has non-zero off-diagonal entries and the corresponding functions are coded to implement the two-terminal inertial mass property.

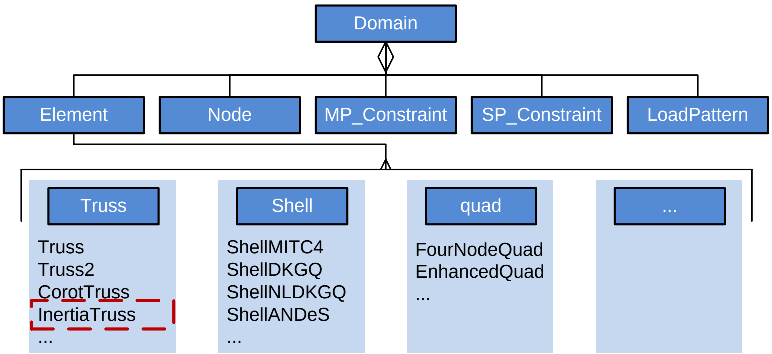


Fig. 6 – InertiaTruss class in OpenSees framework

The InertiaTruss element is calibrated against the experimental data of the TVMD shaking table test conducted by Watanabe et al. [9]. The values of the translational apparent mass m_d, damping coefficient c_d and exponent α, and supporting stiffness k_b of the tested specimen are shown in Fig. 7. In this model, the inerter is modeled by the InertiaTruss element. The damper and supporting spring are modeled by the twoNodeLink elements. The test and time history results are compared in Fig. 8, the numerical analysis tracks the test data well and the InertiaTruss element is proved to be of good accuracy.

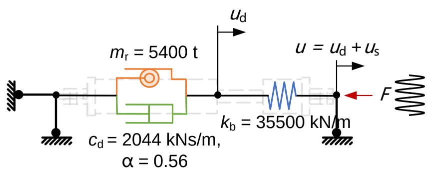


Fig. 7 – Schematic of the analytical model

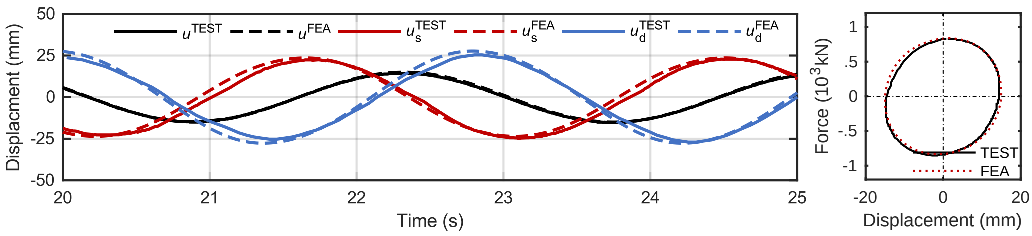


Fig. 8 – Comparison between test and FEA results

3.2 FE model of the TVMD coupled wall

To develop the numerical models for the coupled wall in OpenSees, the RC wall piers and the RC coupling beams are discretized adopting the multi-layer shell elements and link elements, respectively. In the multi-layer shell element, concrete is represented by several concrete layers, and the distributed reinforcement is represented by smeared rebar layers. The longitudinal rebars in the boundary elements are modeled with truss elements, and they are coupled with the surrounding shell elements. Other details and the validation of this multi-layer shell model for wall piers can be found in references [10]. The nonlinear link elements used to represent the simplified numerical model for the RC coupling beams are defined by the twoNodeLink elements with Hysteretic materials. The skeleton of the force-displacement relationship of RC coupling beams is defined per ASCE/SEI 41-17 [11] provision.

The rigid connection between TVMD and wall piers is modeled with additional rigid beam elements that transfer the force developed at the coupling beam end and the TVMD end to shell elements on the same floor. The rigid diagram is simulated by coupling the transverse displacement DOF of the nodes on the same floor. The Rayleigh damping model is adopted with the parameters determined by assuming the damping ratios of the 1^{st} and the 3^{rd} mode are equal to 0.05. The floor seismic mass acting on the wall piers is represented by the lumped masses attached to the floor of each story.

4. Nonlinear time history response analysis

4.1 Ground motion selection

As illustrated in Fig. 9, three types of structural systems are modeled and analyzed in this study, namely the TCW, the VCW (viscous damper coupled wall system) and the RCW. The VCW system discussed here is a structural system in which the TVMDs are replaced by the viscous dampers (VDs) which have identical damping parameters as those TVMDs. This system can also be approximately formed by letting $k_b \to \infty$ and $m_r = 0$ in the TCW system. The comparison between the responses of the TCW system and VCW system is conducted to indicate how the inertial mass and spring behaves when the TVMD is optimally tuning designed and to figure out TVMD's advantage over VD.

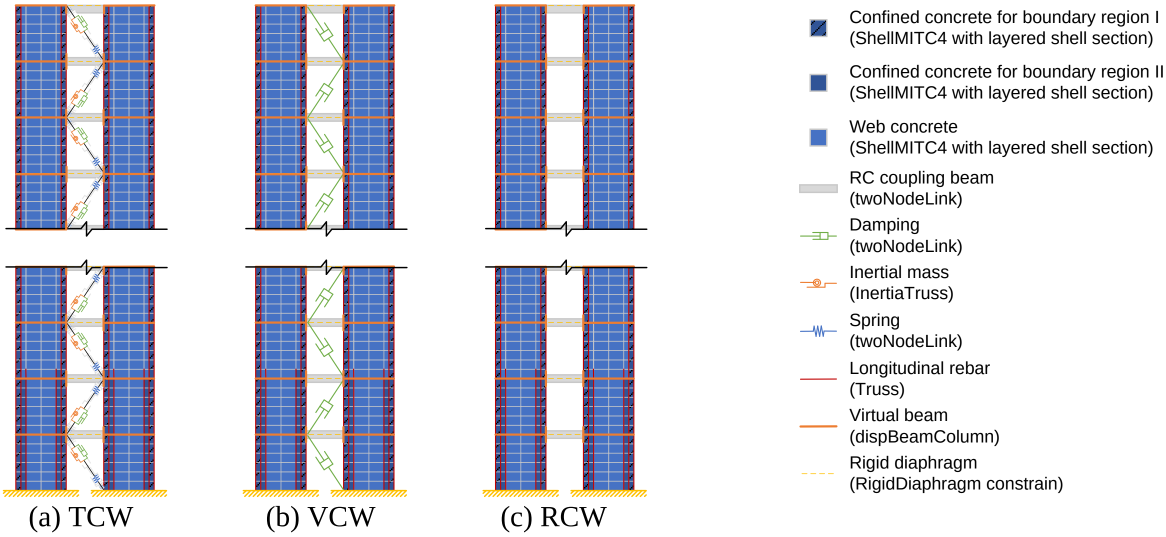
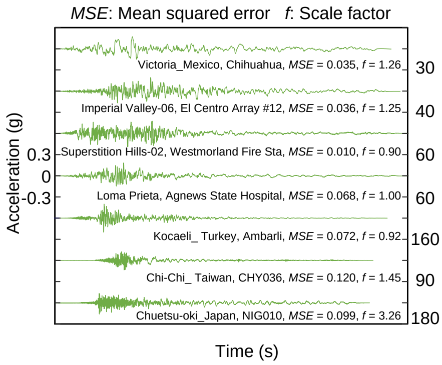
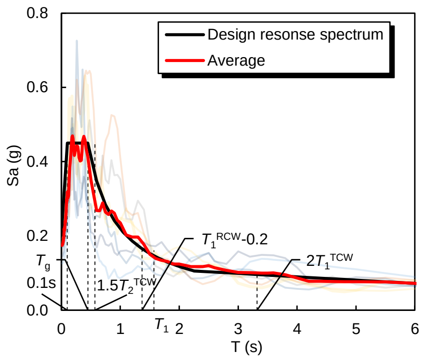


Fig. 9 – Schematic of models for nonlinear time history analysis

Seven ground motions are selected from PEERs NGAS West 2 Ground Motion Database [12]. The target spectrum is the DBE response target spectrum specified in GB 50011-2010 (assuming damping ratio of 5%) and the linear scaling method is used to minimize the mean square error (MSE) of the ground motions' acceleration response spectra with respect to the target spectrum over the period range of interest (Fig. 10). The period range of interest is selected to span [0.1 s, $1.5T_2^{TCW}$] and [T_1^{RCW} - 0.2, $2T_1^{TCW}$], where T_1^{RCW} and T_1^{TCW} is the period of the first mode of the RCW and TCW model, T_2^{TCW} is the period of the second mode of the RCW model. The characteristic site period T_g = 0.45 s locates within the range of [0.1 s, $1.5T_2^{TCW}$]. In the time history analysis, the amplitudes of selected ground motions of DBE are scaled with a factor of 0.35, 2, and 3.1 to represent the seismic motions of SLE, maximum considered earthquake (MCE, with a probability of exceedance of 2% in 50 years), and very rare earthquake (VRE, with a probability of exceedance of 0.5% in 50 years), respectively.



(a) Acceleration time histories of selected motions



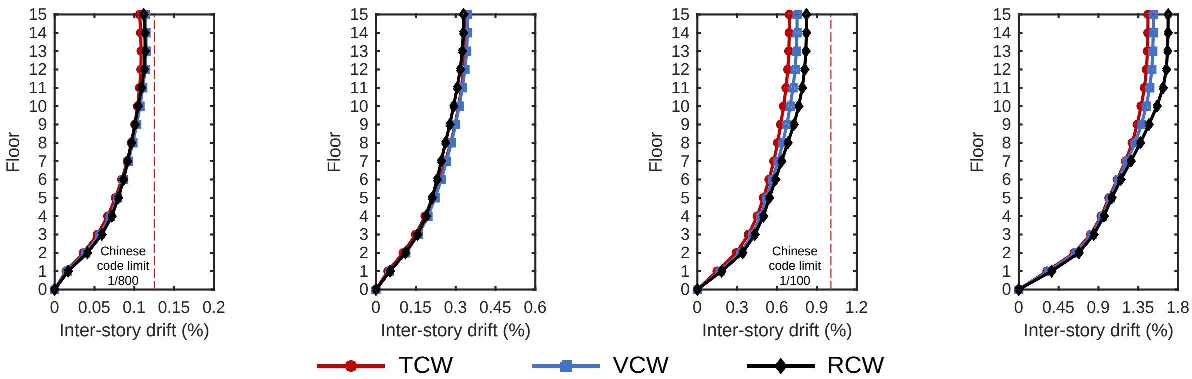
(b) Acceleration response spectra

Fig. 10 – Selected ground motion records and response spectra

4.2 Dynamic analysis results

4.2.1 Responses of inter-story drift

Fig. 11 compares the peak transient inter-story drift distribution of the TCW, VCW, and RCW system. Their inter-story drift responses are almost identical at SLE as a result of the structural design. The maximum drifts at SLE and MCE are smaller than 1/800 and 1/100 (the drift limit required by GB 50011-2010 [5]). The TCW and RCW have similar inter-story drifts at DBE, although the former has higher damping while the latter has higher stiffness. Under MCE and VRE, The TCW shows better control of drift response, and its maximum inter-story drifts are 15.7% and 13.5% smaller than those of the RCW. As the TVMDs are tuned to the 2nd mode and the vibration control ability is not concentrated on the 1st mode which has the dominant contribution to the drift responses. Therefore, the maximum inter-story drifts of the TCW are only 2.6% to 7.8% smaller than those of the VCW for the four intensities of ground motions.



(a) SLE (b) DBE (c) MCE (d) VRE

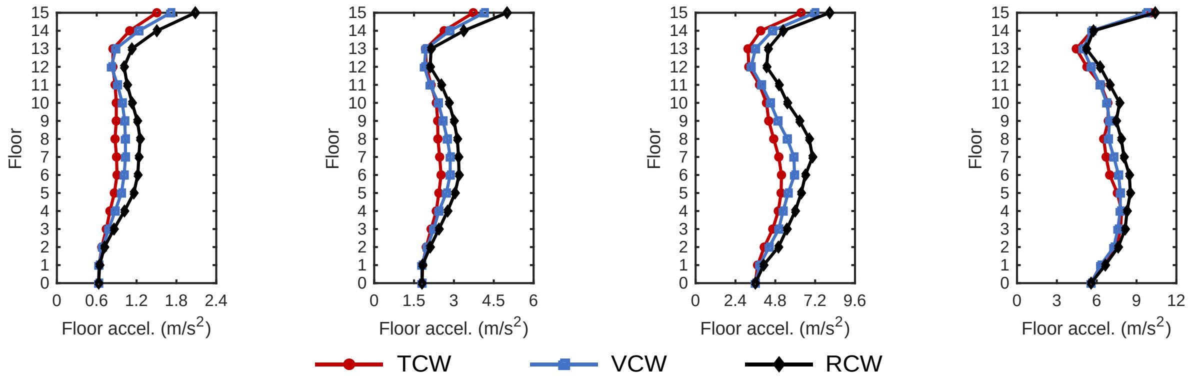
Fig. 11 – Mean values of peak inter-story drift responses

4.2.2 Responses of floor acceleration

Fig. 12 compares the peak floor accelerations at each floor of three models. The maximum accelerations of the TCW are 27.8%, 25.4%, 21.3%, and 2.9% smaller than those of the RCW when subjected to SLE, DBE, MCE, and VRE, respectively. Two aspects of reasons contribute to the acceleration control of the TCW structural system. The first reason is the damping enhancement. The TVMDs add large damping to the 2nd mode of the primary structure, which helps to suppress the acceleration response. Besides, the RC coupling beams in the TCW system are less stiff than those in the RCW system, which leads to the lower lateral stiffness of the system and corresponding lower acceleration.

The RCW is more damaged compared with the other two systems at VRE, and its stiffness reduction leads to a reduction of acceleration response amplification as observed in Fig. 12. As such, the reduction of floor acceleration of the TCW is less significant than the RCW at VRE. Nevertheless, the control of floor acceleration is commonly highlighted in SLE and DBE for the protection of nonstructural components, while it may not be seriously considered for the VRE in which the design target is for collapse prevention.

For the comparison of the TCW and VCW, the difference between their acceleration responses is more obvious than that between their displacement responses. Relative to the VCW system, the TCW system has better control of accelerations at top and middle stories, which coincides with the mode shape of the 2nd mode. The peak floor accelerations of the TCW are up to 15.3% and 15.4% smaller at top and middle stories. The observation indicates the inertial masses (inerter) and supporting springs can help to enhance the acceleration control when they are optimally tuning designed to the 2nd mode of the primary structure.

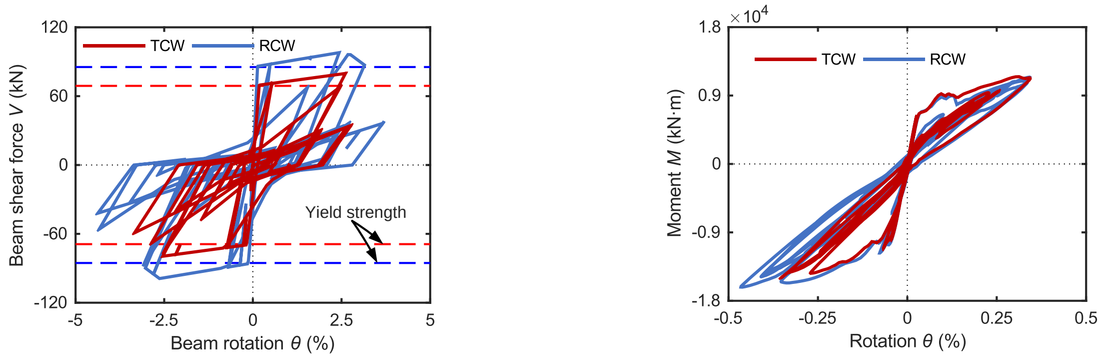


(a) SLE (b) DBE (c) MCE (d) VRE

Fig. 12 – Mean values of peak floor acceleration responses

4.2.3 Responses of typical components

Fig. 13 compares the shear force versus rotation hysteretic curves of the RC coupling beam at the top story and the moment versus plastic hinge rotation hysteretic of the left wall pier (the length of the plastic hinge is taken as 0.5 times the wall depth per ASCE/SEI 41-17 [11] provision) in the TCW and RCW model at VRE. The beam rotation of the RCW is larger and the maximum beam rotation is 4.4%, which indicates more severe damage to the beam. The hysteretic curve of the wall pier also shows the RCW has large plastic rotation in the wall base.



(a) Coupling beam at the top story (b) Left wall pier

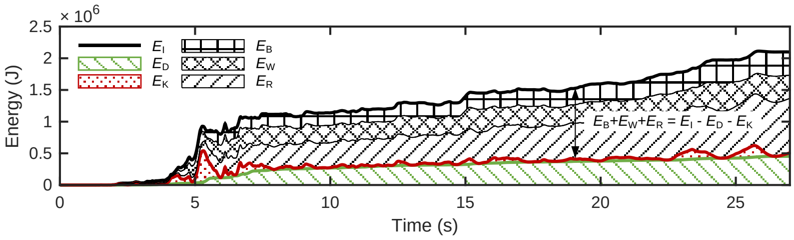
Fig. 13 – Hysteretic curves of typical components (Victoria-Mexico earthquake @ VRE)

4.3 Vibration control mechanism

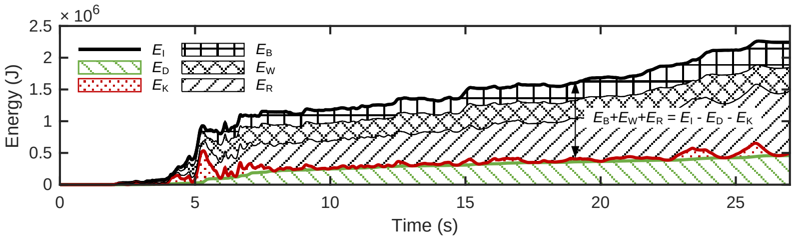
4.3.1 Displacement control mechanism

The displacement responses of the coupled wall in the TCW and VCW system are primarily controlled by the energy dissipation of TVMDs and VDs. Fig. 14 illustrates the energy time history responses obtained with the nonlinear analysis data of the Victoria-Mexico earthquake (at MCE). E_I denotes the input energy by the earthquake. E_K denotes the kinetic energy of wall piers. E_D denotes the dissipated energy of TVMDs or VDs. E_B and E_W denote the dissipated hysteretic energy of coupling beams and wall piers. E_R is the energy dissipated by the inherent Rayleigh damping of the system. The total input energy of the TCW, VCW, and RCW system are 2.10×10^6 J, 2.24×10^6 J, and 2.43×10^6 J in the end of the motion. The values of E_D of the TCW and VCW are similar (4.55×10^5 J and 4.59×10^5 J), which coincides with the observation that TVMD doesn't show significant advantages over the VD for the displacement control. The TVMDs dissipate nearly 20% of the input energy. Correspondingly, E_B and E_W are reduced by 39% and 56% in the TCW system compared with those in the RCW system.

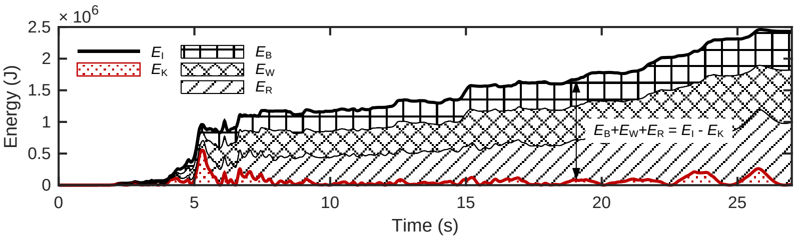
The previous study [1] has shown that when a TVMD is tuned to the first mode of the primary structure, the ball screw device and the supporting spring deform in the opposite directions during the tuning vibration of the TVMD, which amplifies the deformation of the ball screw device and enlarges the energy dissipation. However, in this case, the target mode is chosen to be the 2nd mode, and the displacement control by the TVMD does not have specific benefits from tuning design, relative to VDs. The energy dissipations and inter-story responses of TVMDs and VDs are similar.



(a) TCW



(b) VCW



(c) RCW

Fig. 14 – Energy dissipation (Victoria-Mexico earthquake @ VRE)

4.4.2 Acceleration control mechanism

The hysteretic curves of the damper forces are compared in Fig. 15, in which the blue line represents the force of the VD in the VCW system, the red line represents the force of the TVMD in the TCW system and the gray dash line represents the force of the viscous damper only in that TVMD. The force of the TVMD is approximately three times as large as the damper force of the VD, although the amplitudes of their displacement are similar. Fig. 16 illustrates the decomposition of the time history responses of the top floor accelerations of the TCW and VCW, and the forces of TVMD and VD in the top story. The floor accelerations or the damper forces of the 1st, 2nd, and higher-order modes are obtained using the filter with the frequency ranges of [$0.8/T_1^{TCW}$, $1.2/T_1^{TCW}$], [$0.8/T_2^{TCW}$, $1.2/T_2^{TCW}$], and [$0.8/T_3^{TCW}$, $+\infty$), respectively. A 3-order Butterworth filter is used for calculation. As shown in Fig. 16 (a), both the 1st and 2nd modes significantly contribute to the floor accelerations. The control forces of TVMD and VD also concentrate on the two lower-order modes and have a limited contribution to the higher modes. Both systems show similar acceleration responses in the 1st mode, and the forces provided by TVMD and VD in this mode are nearly identical. Due to the tuning design to the 2nd mode, the TVMDs provide significantly higher force than the VDs, and they can suppress the acceleration response of the 2nd mode more effectively. As the 2nd mode often has high contributions to the floor acceleration response of high-rise buildings, the TCW system using 2nd mode tuning design has the advantage for acceleration response control over the TCW system.

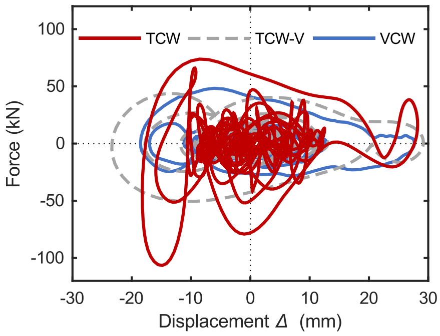
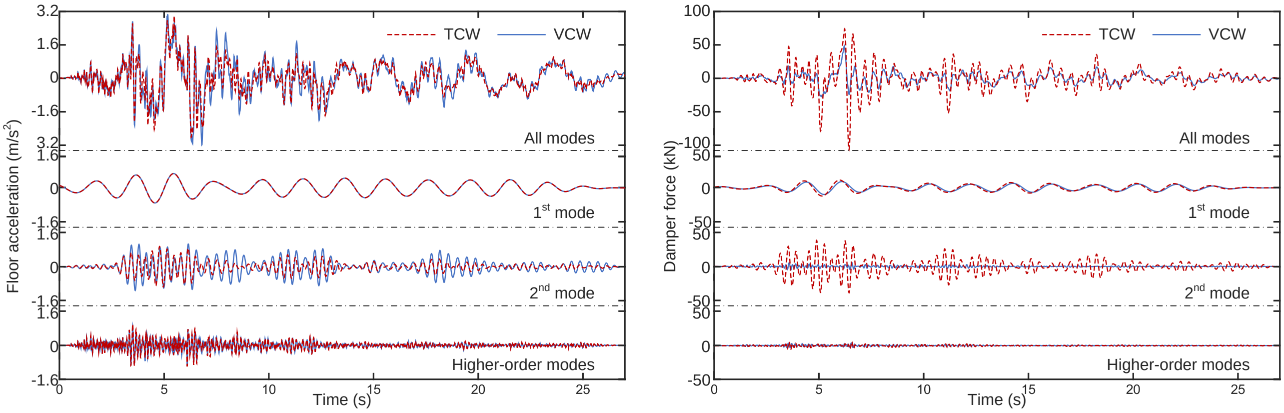


Fig. 15 – Hysteretic curves of the damper force (Victoria-Mexico earthquake @ DBE).



(a) Floor acceleration and modal decomposition (b) Damper force and modal decomposition

Fig. 16 – Decomposition of the top floor accelerations and damper forces in the top story (Victoria-Mexico earthquake @ DBE)

5. Conclusion

This paper studies the seismic responses of an innovative tuned viscous mass damper (TVMD) coupled wall (TCW) system via finite element (FE) analysis. The nonlinear FE model of a representative TCW structural system in a 15-story high-rise building is developed via OpenSees in which a newly compiled element named InertiaTruss is implemented to simulate the behavior of the TVMD. The nonlinear responses of inter-story drift and floor acceleration of the TCW, viscous damper coupled wall (VCW) and RC coupling beam coupled wall (RCW) models are obtained and compared.

When the mass ratio is set to be 0.1 and the TVMDs are tuning designed to the 2nd mode, the peak inter-story drifts of TCW system are up to 8% and 16% smaller than those of the VCW and RCW system. The peak floor accelerations of the TCW system are up to 15% and 28% smaller than those of the VCW and RCW system. The analysis results indicate the vibration control mechanism of inter-story drifts is associated with the energy dissipation of TVMDs, whereas the control of floor accelerations is attributed to significantly suppressing the 2nd mode vibration by the tuning effect.

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