



DEVELOPMENT OF DOUBLE-YIELD COUPLING BEAM DAMPER FOR SEISMIC RESILIENT PRECAST SHEAR WALL STRUCTURE

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Abstract

RC Shear wall structure system is widely used in China for residential buildings for its architecture friendliness and seismic superiority. Precast RC shear wall structure associated with energy dissipation device is developing rapidly in China aiming at realizing a higher construction industrialization and seismic resilience level. In this paper, a novel double-yield coupling beam damper is proposed. Two main energy dissipation elements are combined in this damper. One is viscoelastic damper, the other is steel shear damper. A displacement limit element is installed in this system to realize double-yield mechanism. Finite element analysis was conducted in ABAQUS to validate the construction's performance. The initial and second stiffness are calculated and the hysteretic curve is illustrated to guide the damper design. The responses of prototype precast shear wall structure installed with double-yield coupling beam damper and ordinary steel shear damper under different intensity earthquakes were also simulated. The results showed that the damper can reduce both the acceleration and deformation response of the structure under frequency earthquake to protect the non-structural components, and can also control the displacement of the structure under rare earthquake compared to ordinary steel shear damper, which contributes to the seismic resilient of precast shear wall structure.

Keywords: double-yield, coupling beam, damper, seismic resilient, precast shear wall structure



1. Introduction

Dampers have been widely used in building structures to improve the seismic performance since it is proposed. [1] It is the vital device to realize energy dissipation and seismic mitigation design concept. Dampers can provide additional damping and stiffness to the structure, so that the building displacement or acceleration can be reduced under the same earthquake. Totally displacement dependent dampers, such as buckling restrained brace, friction damper and steel shear damper, can provide both damping and stiffness at the same time after yielding. Totally velocity dependent dampers, such as viscous damper, provide only damping related to the velocity. Viscoelastic damper is both dependent to displacement and velocity, so that it can dissipate energy once the displacement happened as well as providing additional stiffness. Xu et.al [2] studied the performance of the viscoelastic damper installed into the seismic retrofit building by elasto-plastic time history analysis. The results showed that the viscoelastic damper can reduce the displacement response and the rotation effect at the same time. Shear wall structures get large stiffness and the deformation mainly focus on the coupling beam. So that coupling beam has been investigated to replace with shear type damper. Ji et.al [3] proposed a kind of replaceable steel coupling beam damper, the damper can deform under 0.06 rad and got stable energy dissipation capacity. Wang et.al [4] studied the high damping viscoelastic coupling beam damper by quasi-static test, and the results showed that the damper can enhance the stiffness of the shear wall structure and reduce the seismic response as well. With the seismic resilience building comes to the target of structure engineering and earthquake engineering development, mitigating response of displacement as well as acceleration are both important in the real project. Most non-structural components' damage states are influenced by storey acceleration. The damage of non-structural components will definitely enlarge the cost and time before the building recover to the normal function. [5] Large stiffness damper such as steel shear damper can reduce the displacement response under large earthquakes, however the acceleration response could not reduce easily under frequency earthquakes. The viscoelastic damper could provide energy dissipation under frequency earthquakes; however, the bearing capacity and energy dissipation are not easy to enhance restricted to the installation space. Double yield type dampers, such as double-yield buckling restrained brace, double sliding friction damper, double yielding steel coupling beam are proposed by Pan et al [6-8] to control the storey drift ratio distribution and improve energy dissipation efficiency of frame or shear wall structures. The analysis results show that the double yield type dampers could effectively control the deformation patterns of structures and reduce the probability of weak storey collapse of frame structures. This concept can also be used into the shear wall structures. This paper proposed a novel double-yield coupling beam consisting of viscoelastic damper and steel shear damper. The construction details are firstly illustrated, and refined finite element model is built to validate the double yield performance. The stiffness and bearing capacity formula are derived to design the double-yield coupling beam. Elasto-plastic time history analysis is conducted to validate the effect of reducing acceleration and displacement response under different intensity of earthquakes.

2. Innovative concept

Fig. 1 shows the configuration of the proposed double-yield coupling beam damper. The damper mainly consists of two energy dissipation cells, one is steel yielding cell, and the other is viscoelastic cell. The viscoelastic cell consists of rubber and steel plates. The rubber is pasted on the steel plate. The steel plates move relatively and cause the rubber deform. The viscoelastic cell gets relative lower shear stiffness and bearing capacity. It deforms and dissipates energy under the design deformation of the structure under frequency earthquakes, so that it can provide energy dissipation and reduce the structure's deformation and acceleration. Once the viscoelastic damper deforms beyond the design value, the stop element is activated. The stop element is designed with large stiffness, and it can restrict the shear deformation of viscoelastic damper in a design range both in positive and negative direction. The stop element restricts the deformation of the damper in the axial direction at the same time. After the stop element is activated, the deformation concentrates at the steel yielding cell. The steel yielding cell gets larger bearing capacity, and can provide

both stiffness and energy dissipation for the structure under rare earthquakes. In summary, the damper can provide additional stiffness and energy dissipation both in frequency and rare earthquakes.

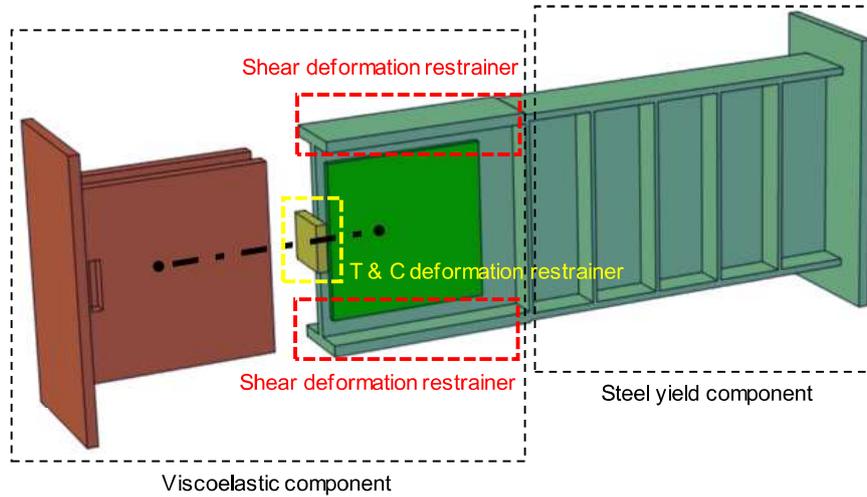
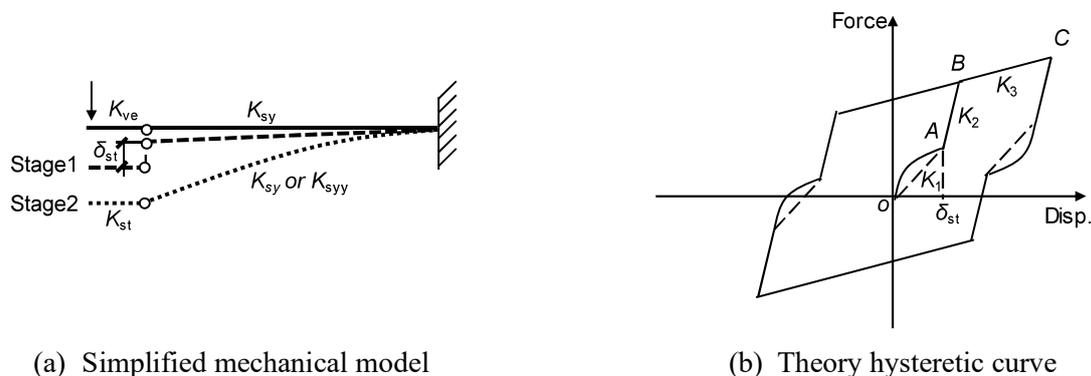


Fig. 1 – Proposed double-yielding coupling beam

3. Design method

The damper can be simplified by different stiffness springs' combination as shown in Fig.2 (a). The deformation of the damper can be divided into two stages. The first stage's deformation concentrates at the viscoelastic cell. The second stage's deformation concentrates at the steel yielding cell. The shear stiffness of viscoelastic cell, the stop cell and steel yielding is K_{ve} , K_{st} and K_{sy} , correspondingly. The stiffness of the steel damper after yielding is K_{syy} . The gap size is δ_{st} . The hysteretic curve is shown in Fig.2 (b). K_1 is the total shear stiffness in the first stage. It can be calculated by Eq. (1). K_2 is the total shear stiffness in the second elastic stage. It can be calculated by Eq. (2). K_3 is the total shear stiffness in the second plastic stage. It can be calculated by Eq. (3). From these equations above, the damper can be designed according to the building requirement. The gap size is determined by the deformation of the coupling beam damper under frequency seismic design requirement. In China, the storey drift ratio limit of shear wall structure is 1/800 under frequency earthquake.



(a) Simplified mechanical model

(b) Theory hysteretic curve

Fig. 2 – Simplified model and hysteretic curve

$$K_1 = \frac{K_{ve} K_{sy}}{K_{ve} + K_{sy}} \quad (1)$$



$$K_2 = \frac{K_{st} K_{sy}}{K_{st} + K_{sy}} \quad (2)$$

$$K_3 = \frac{K_{st} K_{syy}}{K_{st} + K_{syy}} \quad (3)$$

4. Finite element analysis

4.1 Refined finite element model

To validate the construction of the double-yield coupling beam damper, a refined finite element model is built in ABAQUS. Fig.3 shows the dimensions of the finite element specimens.

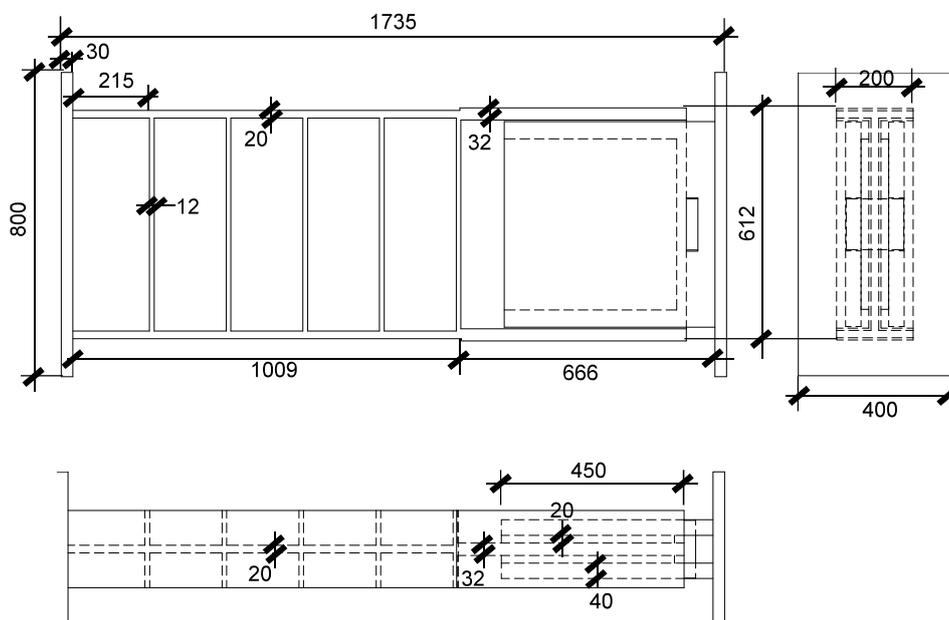
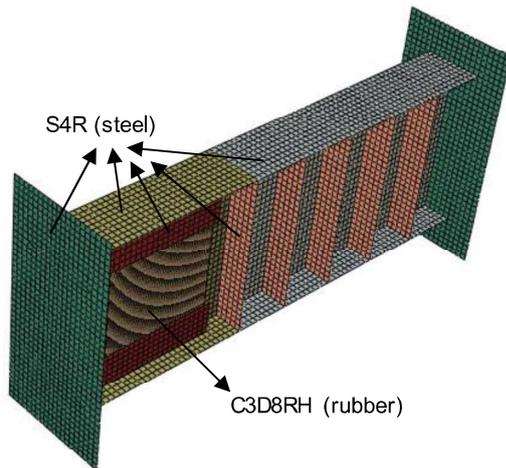


Fig. 3 – Dimensions of finite element specimen

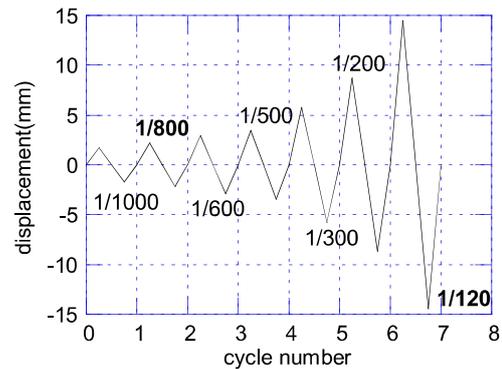
As shown in Fig. 4, the model is combined by different parts and elements. The steel yielding cell is simulated by S4R shell element. This element has 4 nodes with reduced integration. The steel plate in the viscoelastic damper element is also simulated by S4R element. The rubber between the steel plates is simulated by solid element C3D8RH. This element is 8-node three-dimensional element with reduced integration considering hybrid effect. The rubber surface is constraint with the steel plate surface by TIE method [9]. By TIE method, the nodes which are close in distance, are coupled together in the contact pair surfaces. The stop and axial constraint mechanisms are simulated by interaction. The axial mechanical property is hard contact. When the side plate of viscoelastic damper element contacts with the side plate of the stopper element, the contact stiffness is infinity large, and when the side plate moves apart from the stopper element, the contact force becomes zero. The Mooney-Rivlin [10] form is used to simulate the hyper-elastic behavior of the viscoelastic rubber. The values to fit the math parameter are got from the test results of typical rubber material used in viscoelastic damper [11]. The hysteretic parameter is referred to the result of J.S. et.al [12]. The constitutive model of the steel plate is bilinear kinematic hardening model. The elastic modulus is 200000MPa. The yield strength is 400MPa, and the post-yield stiffness is 2000MPa. Static loading rules as shown in Fig. 4(b) are applied on the specimen. 1/800 and 1/120 are the drift limit of shear wall structure under frequency and maximum considered earthquake, respectively, according to the design



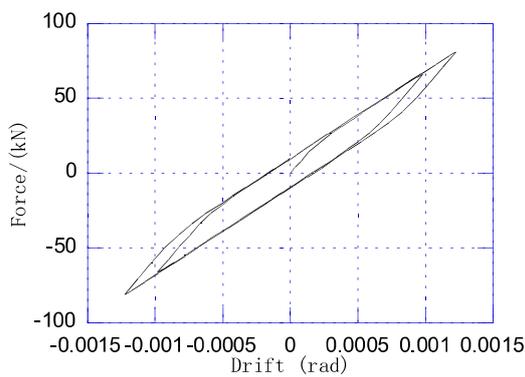
code of China. [13] The hysteretic results got by finite element analysis is shown in Fig. 4 (c) and (d). The hysteretic curve of the specimen under 1/800 drift ratio shows pure viscoelastic behavior. After 1/800 drift ratio, the steel yielding cell functions and yields at 1/400 drift ratio. The hysteretic curve shows apparent double-stage property, which validates the effectiveness of the construction.



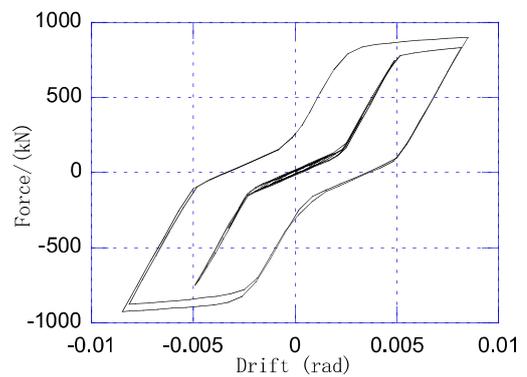
(a) Refined finite model



(b) Loading history



(c) Hysteretic curve under 1/800 drift ratio



(d) Hysteretic curve under 1/120 drift ratio

Fig. 4 – Refined finite element model, loading history and hysteretic curve

4.2 Simplified finite element model

A simplified model is built to simulate the behavior of the double-yield coupling beam damper. The simplified model is shown in Fig. 5(a). The connector with corresponding property is used to simulate the viscoelastic cell and steel yielding cell. For the viscoelastic connector, the elastic stiffness is set to 6×10^7 N/m and the damping coefficient is 1×10^6 N/(m/s). The steel yielding connector is set the same corresponding elastic modulus, yield strength and post-yield stiffness as the refined model parameter. The connector with nonlinear elastic axial property is used to simulate the stopper mechanism as shown in Fig. 5(b). In the deformation of 3 mm range, that is the gap size, the connector's force is almost zero. Beyond the range, the connector's force becomes extremely large, and the stiffness is set according to the dimension of shear deformation restrainer. The related length dimensions are the same with the refined model. The hysteretic curve of the simplified model shows in Fig. 5(c) and Fig. 5(d). The behavior of the simplified model under 1/800 drift ratio is also like viscoelastic behavior, however, the energy dissipation capacity is less for the loading velocity is rather low. However, the behavior of the model under 1/120 fits well with the



result of the refined finite element model. So that the simplified model can be used to do time history analysis combined with the shear wall structure.

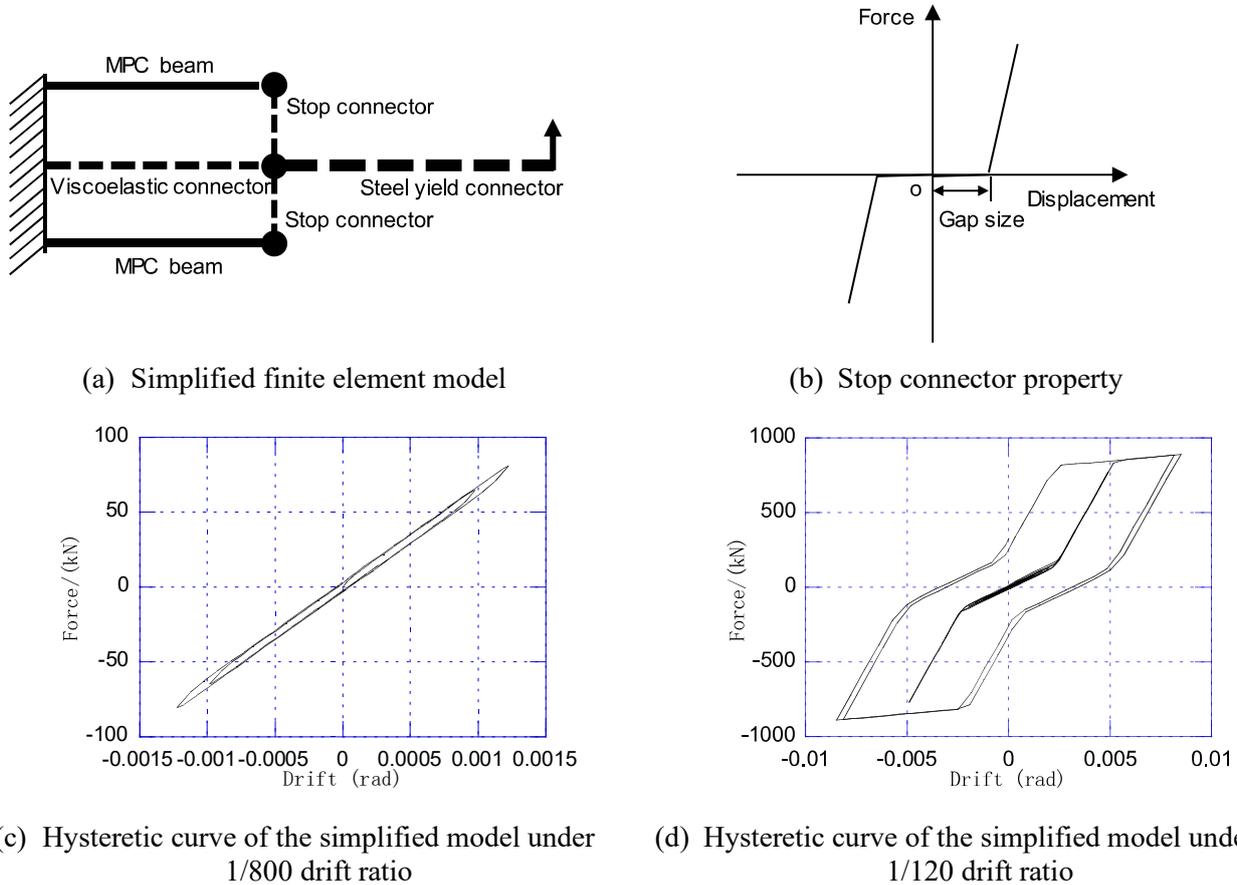


Fig. 5 – Simplified finite element model and hysteretic curve

4.3 Elasto-plastic time history analysis

To validate the seismic response mitigation performance of the double-yield coupling beam damper, a prototype shear wall building [14] is chosen as the basic model. Fig. 6 shows the dimensions and reinforcement arrangement of one piece side coupled shear wall in the prototype building.

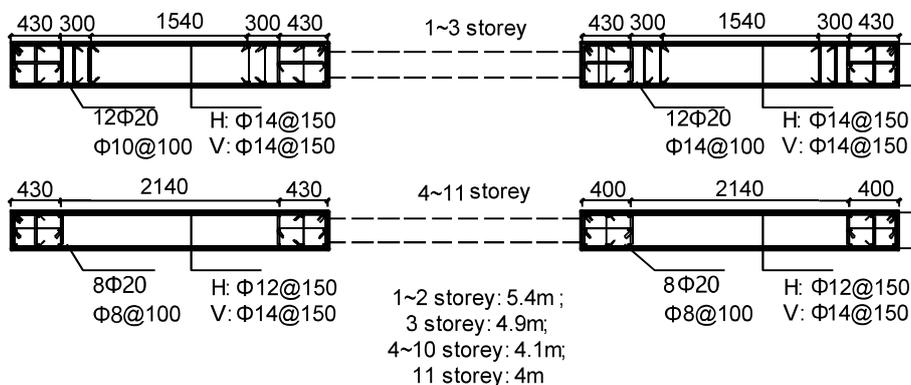


Fig. 6 – Prototype coupling shear wall dimensions



The concrete is C30 with 30 MPa axial compression stress. The rebar is HRB400 type, with 400 MPa yielding stress. This side coupled shear wall model is built in ABAQUS as shown in Fig. 7. The wall panel is simulated by B31 element, and the reinforcement of the shear wall is inserted into the beam element section by “rebar” method. PQ-fiber [15], a series of constitutive user material models for steel and concrete, is used. Usteel02 constitutive model is used to simulate the reinforcement in the shear wall, which is double linear hysteretic model considered stiffness degradation under repeat loading proposed by Clough [16]. Uconcrete01 constitutive model is used to simulate the concrete in the shear wall, and the coupling beam is simulated by connectors.

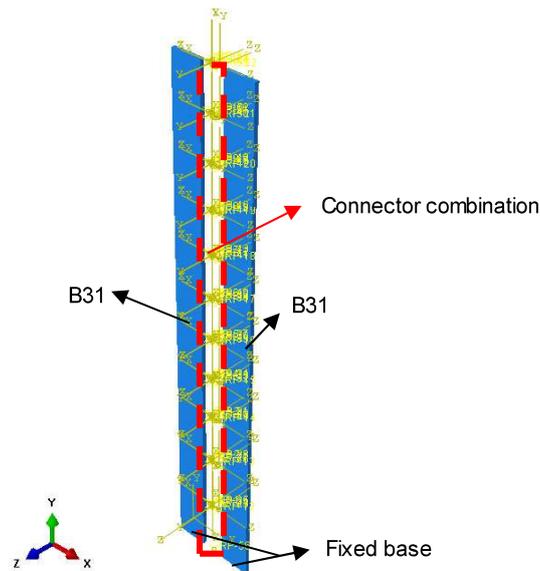
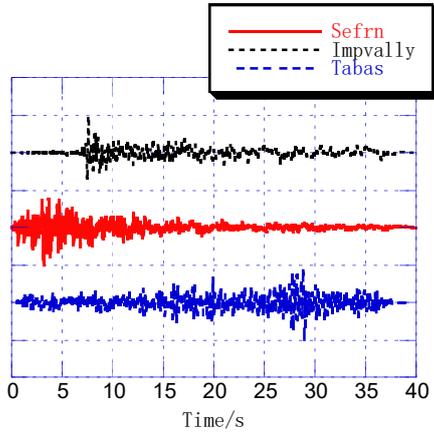
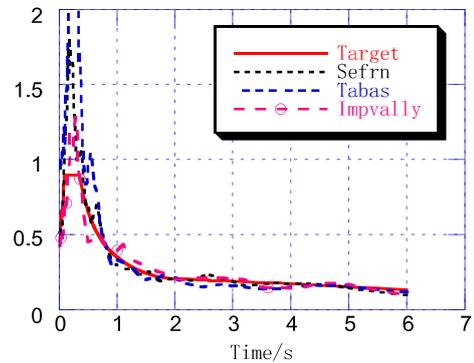


Fig. 7 – Coupling shear wall model in ABAQUS

Two kinds of coupling beam damper are chosen for the comparison. One is the proposed double yielding damper, the other is the ordinary steel yielding damper. The elastic modulus of the viscoelastic cell in the double yielding damper is 1×10^8 N/m, and the viscous coefficient is 1×10^6 N/(m/s). The stop gap is 1mm, and the gap closed stiffness is 2×10^{10} N/m. The elastic modulus of the steel yielding damper is 1.4×10^8 N/m, and the post-yield stiffness is 5×10^6 N/m. The stiffness of the ordinary steel yielding damper is the same as the steel yielding cell in the double yielding damper. The first period of the structure installed with double yielding damper and ordinary steel damper is 1.12 s and 0.96s correspondingly, both under horizontal deformation. Three real ground motion records are chosen from PEER earthquake ground motion database [17] as shown in Fig. 8. Fig. 8(a) shows the normalized time-acceleration curve of the three ground motions. Fig. 8(b) shows the acceleration spectrum comparison of the target spectrum and the ground motions' spectrum. The records are amplitude modulated to the level of frequency and maximum earthquake level with maximum acceleration 0.7m/s^2 and 4m/s^2 , respectively.



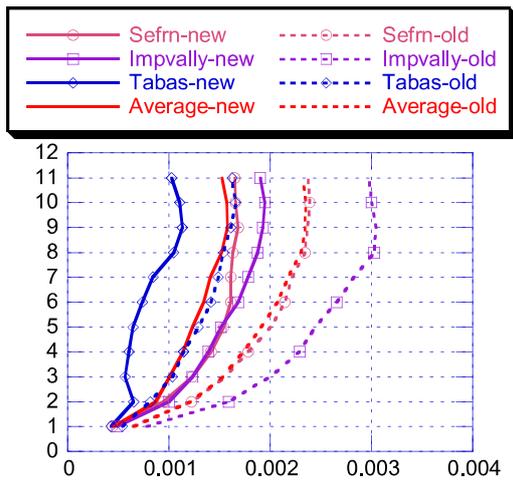
(a) acceleration of ground motion records



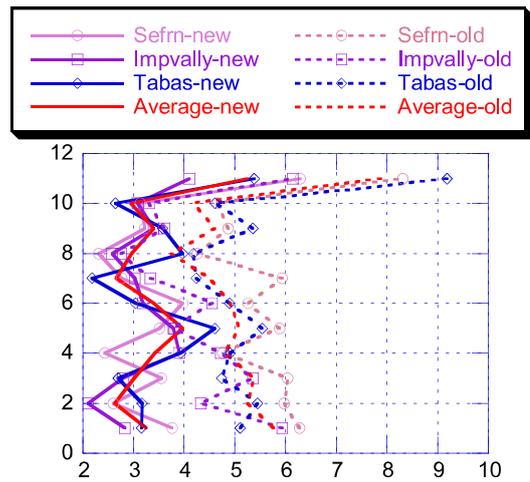
(b) spectrum of ground motion records

Fig. 8 – Earthquake records for time history analysis

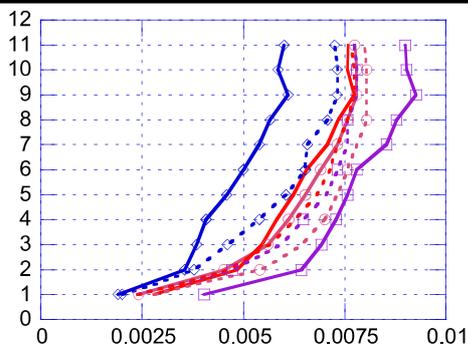
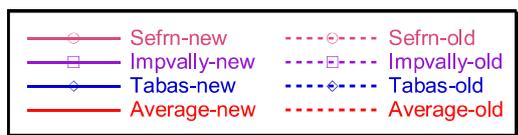
Fig. 9 shows the comparison of the two coupling shear wall in the aspect of storey drift ratio and acceleration under frequency and maximum considered earthquakes.



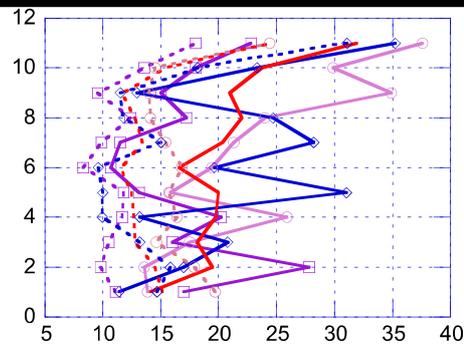
(a) Storey drift ratio comparison under frequency earthquakes



(b) Storey acceleration comparison under frequency earthquakes



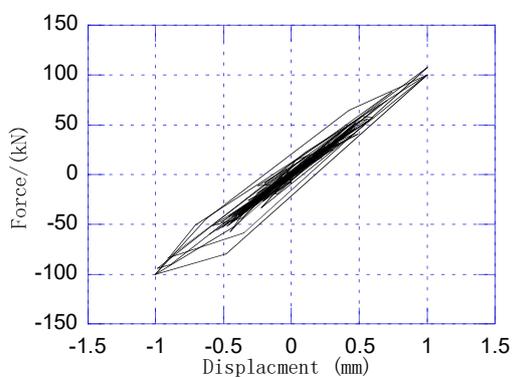
(c) Storey drift ratio comparison under maximum considered earthquakes



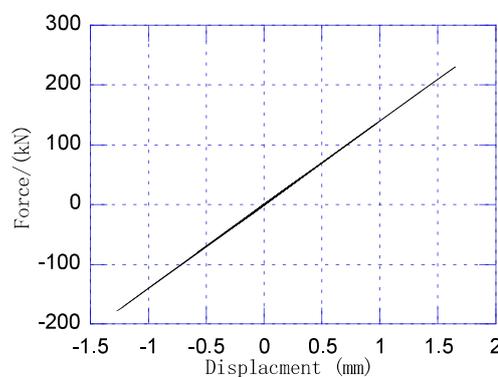
(d) Storey acceleration comparison under maximum considered earthquakes

Fig. 9— Comparison of drift ratio and acceleration of two models under frequency and maximum considered earthquakes

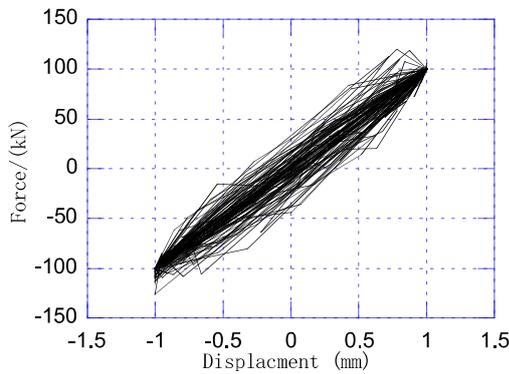
As shown in Fig. 9(a), “-new” means shear wall installed with double yielding damper, and “-old” means ordinary steel yielding damper. The drift ratio of the storey of new shear wall is smaller than that in the old shear wall under all ground motions. The largest average drift ratio is 0.0023 in old shear wall and the largest drift ratio is 0.0016 in new shear wall. The drift ratio is reduced 30%. As shown in Fig. 9(b), the maximum average acceleration of the old shear wall is 8.3 m/s^2 , and it is 5.4 m/s^2 in new shear wall. The acceleration is reduced 35%. The reason is that the extended period as well as the additional viscous energy dissipation reduce the response of the structure under earthquakes. Under the maximum considered earthquakes as shown in Fig. 9 (c) and (d). The drift ratio is almost the same in the average, however, the acceleration of the new shear wall is larger than that in old shear wall. The reason is that the energy dissipation of ordinary steel yielding damper dissipates more energy than the double yielding damper under the maximum considered earthquakes, so that the acceleration is also smaller. The hysteretic curves of double yielding damper’s viscoelastic damper and steel yielding damper of storey 2 under Tabas ground motions are shown in Fig. 10. Under the frequency earthquakes, the steel yielding damper is not activated, however, the viscoelastic damper starts dissipating energy. Under maximum considered earthquakes, the viscoelastic damper dissipates more energy, and the steel yielding damper also comes to yield and dissipates energy.



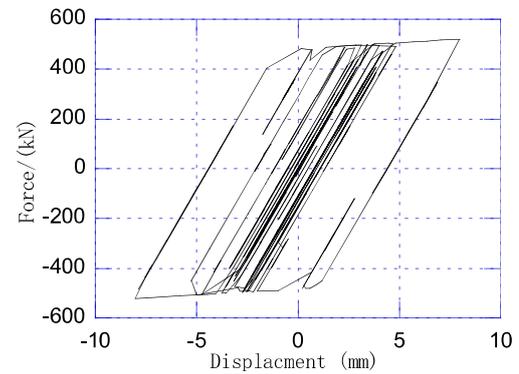
(a) Viscoelastic damper under frequency earthquakes



(b) Steel yielding damper under frequency earthquakes



(c) Viscoelastic damper under maximum considered earthquakes



(d) Steel yielding damper under maximum considered earthquakes

Fig. 10– Hysteretic curve of viscoelastic damper and steel yielding damper under frequency and maximum considered earthquakes (Tabas, 2nd Storey)

5. Conclusions

This paper proposed a novel double-yield coupling beam damper. It is combined with viscoelastic cell and steel yielding cell. The refined construction of the damper is designed and validated by finite element analysis. Time history analysis is conducted to study the influence of the new damper. The main conclusions are shown as followings:

- (1) The construction can realize the double yielding behavior of the damper, and it is validated by refined finite element model as well as simplified model.
- (2) The stiffness formulations are derived by series spring model to guide the design of the double yielding coupling beam damper.
- (3) Time history analysis shows that the double yielding damper can reduce the acceleration and the drift ratio of shear wall buildings under frequency earthquakes by additional energy dissipation, which is good for the seismic resilience of the building under small earthquakes.
- (4) Under maximum consider earthquakes, the drift ratio of the shear wall installed with the double yielding beam could also controlled as the ordinary steel yielding damper, however the acceleration becomes larger.

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