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Study of Earthquake Resilient RC Shear Wall Structures

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Abstract

Proposed in this study is a new type of earthquake resilient reinforced concrete (RC) shear wall structure, installed with replaceable coupling beams and replaceable corner components at the bottom of wall piers. At first, the mechanical behavior of replaceable components, such as combined dampers and replaceable corner component, were studied by running cyclic loading tests. Then, cycling loading tests were conducted on one conventional coupled shear wall and one new type of coupled shear wall with replaceable components. The test results indicated that the damage of the new type of coupled shear wall concentrated on replaceable components while the left parts were well protected. Finally, a case study is introduced. The responses of one conventional frame-tube structure and one new type of structure installed with replaceable components under the wind and the earthquake are compared, which verify that the performance of new type of structure is much better than the conventional structure.

Keywords: RC shear wall, Replaceable corner component, Replaceable coupling beam, Seismic performance, Earthquake resilient structure

1. Introduction

RC shear wall structures are widely applied in tall buildings around the world. The coupling beams and the bottom corners of wall piers in RC coupled shear wall were damaged seriously, which was found from some earthquakes, such as Wenchuan earthquake (Xiong 2008), Chile earthquake (Carpenter *et al.* 2011) and New Zealand Christchurch earthquake (Kam and Pampanin 2011). It is difficult to restore the function of structure after the earthquake if the structure suffers such kind of damage. To improve the earthquake resilience of RC shear wall structure, some researchers developed all kinds of methods in in recent years.

Most of the previous work focused on developing replaceable coupling beams. Various types of dampers installed at the mid-span of the coupling beam were proposed by different researchers. Velocity-dependent damper, such as viscoelastic damper, installed at the middle of the coupling beam, was developed by Christopoulos (Christopoulos and Montgomery 2013; Montgomery and Christopoulos 2015). Qu *et al.* (2020) developed a friction damper, which consists of brake pads, disc springs, and high-strength bolt. The friction damper exhibited stable hysteretic behavior. Different types of metallic dampers were used in the middle of coupling beams, such as I-shaped steel fuse with diamond hole (Lu *et al.* 2018; Wang *et al.* 2012), I-shaped metallic dampers (Fortney *et al.* 2006; 2007; Ji *et al.* 2016). Not only the behavior of I-shaped metallic dampers was examined, but also the replaceability of the damper were studied (Ji *et al.* 2017). A new combined damper installed in the mid-span of coupling beams was proposed by the authors to reduce the responses of RC shear wall structures under the earthquake as well as the wind (Li *et al.* 2019). To reduce the damage of the bottom corners of wall piers, the authors developed a replaceable corner component. The cyclic loading test on the wall with replaceable bottom corner components was conducted, which verified the improved seismic performance (Liu and Jiang 2017).

In this study a new type of earthquake resilient reinforced concrete (RC) shear wall structure, installed with replaceable coupling beams and replaceable corner components at the bottom of wall piers, is proposed and verified by tests and a case study. This is the first try to adopt two types of replaceable components both in coupling beams and wall piers in order to better improve the earthquake resilience of the structure.

2. Constitution of earthquake resilient RC shear wall

The constitution of the new type of earthquake resilient RC shear wall is shown in Figure 1. The middle of coupling beams and the bottom corners of wall piers are installed with replaceable combined dampers and replaceable

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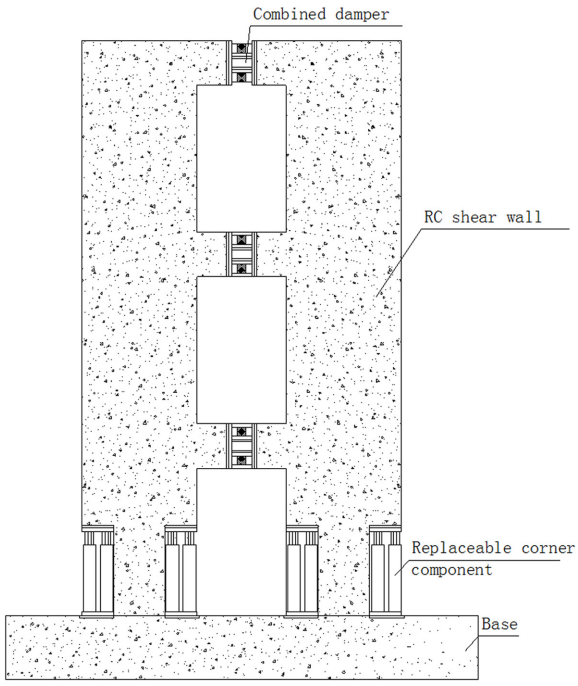


Figure 1. Earthquake resilient RC shear wall with replaceable components.

corner components (RCCs). Under moderate or strong earthquakes, the combined dampers installed in the coupling beam yield and dissipate energy at first, then the RCCs yield and come into play, and the other parts of the coupled shear wall remain elastic. Therefore, the function of the structural wall can be quickly restored by replacing the replaceable dampers and RCCs if damaged after the earthquake.

2.1. Replaceable coupling beam

The replaceable coupling beam consists of the replaceable part (combined damper) in the middle and non-replaceable parts, as shown in Figure 2, Figure 3 shows the schematic drawing of combined damper, which consists of one metallic damper at the center and two viscoelastic (VE) dampers at two edges. Under winds or minor earthquakes, the VE damper dissipates energy and the metallic damper remains elastic to provide initial stiffness and strength. Under moderate or strong earthquakes, the metallic dampers yield and begin to dissipate energy. The non-replaceable part remains elastic.

2.2. Replaceable corner components

Figure 4 illustrates the constitution of replaceable corner

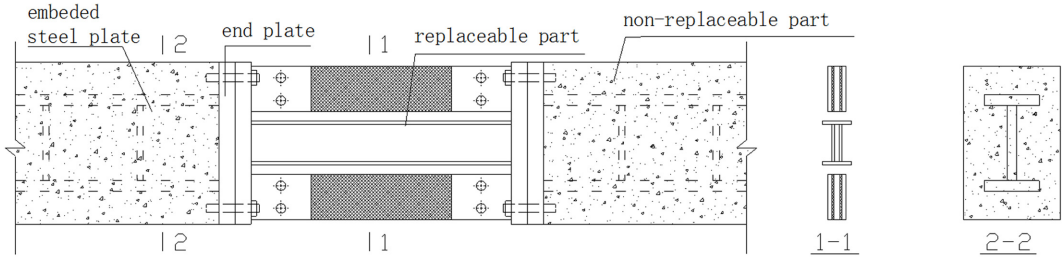


Figure 2. Schematic drawing of replaceable coupling beam.

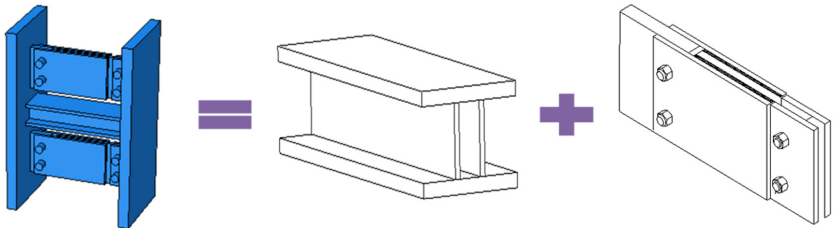
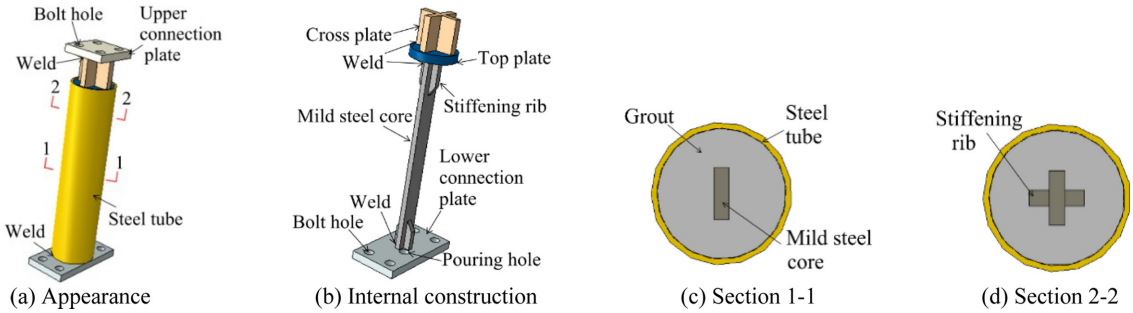


Figure 3. Schematic drawing of combined damper.



(a) Appearance (b) Internal construction (c) Section 1-1 (d) Section 2-2

Figure 4. Constitution of replaceable corner component.

component. RCC consists of a mild steel core and concrete steel tube. The diameter of the top plate is smaller than that of steel tube so that the steel tube does not bear the load directly and it provides restraint on concrete. When the RCC is subjected to compression, the inner mild steel core and concrete work together. Under the tension loading, the inner mild steel core is stretched alone.

3. Cyclic loading test on replaceable components

3.1. Combined dampers

To study the mechanical behavior of the combined damper, cyclic loading tests on the combined damper were conducted. Dimensions of combined damper are shown in Figure 5. The mild steel with the grade of LY225 was used for the web of the metallic damper. The steel with the grade of Q345 was adopted for flange and end plates. The lateral cyclic loading was controlled by displacement with the loading frequency of 0.1 Hz. Figure 6 illustrates the test setup. More details of this test can refer to the reference (Jiang *et al.* 2019).

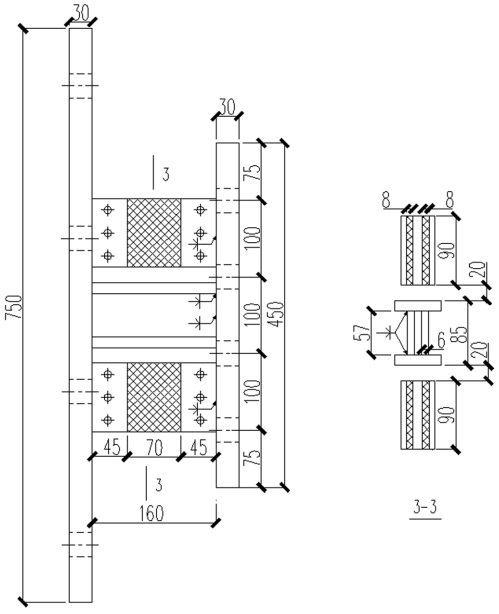


Figure 5. Dimensions of Combined damper.

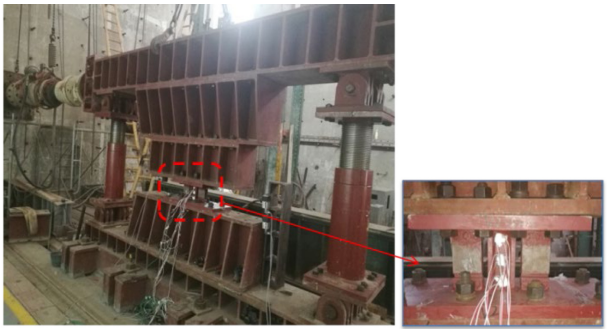


Figure 6. Test setup.



Figure 7. Failure mode of the combined damper.

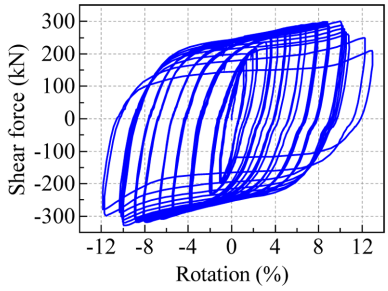


Figure 8. Force versus rotation hysteretic curves.

When the rotation was 8.93%, the crack first occurred in the weld between the flange and the end steel plate. The maximum shear strength of the combined damper was 314 kN, and the corresponding rotation was 9.92%. No damage of the VE damper was observed, as shown in Figure 7. The combined damper exhibited stable hysteretic behavior. The hysteretic curves was S-shaped when the rotation reached about 10%, as shown in Figure 8.

3.2. Replaceable corner components

The RCC was constructed and tested. The length of inner mild steel core was 600 mm. The rectangular cross-sectional dimensions were 55 mm times 6 mm. The mild steel with the grade of LY160 was used for inner steel core. The external diameter of the steel tube was 150 mm, and the thickness was 6 mm. Figure 9 shows the test setup. The specimens were subjected to the axial force. The displacement-controlled cyclic loading was applied on the specimen by the hydraulic actuator.

The specimen failed due to the global buckling. Figure



Figure 9. Test setup.

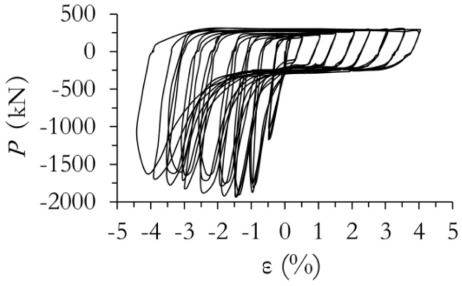


Figure 10. Hysteretic curves.

10 shows the axial force-equivalent strain hysteretic curves. The RCC showed stable cyclic behavior and excellent deformation capacity.

4. Cyclic loading test on earthquake resilient RC shear wall

Based on the mechanical performance test of replaceable components, two 1/2-scaled RC coupled shear wall specimens, including one conventional coupled shear wall named as CW and one earthquake resilient shear wall named as NW, were constructed and tested. The dimensions and steel reinforcement of specimens are presented in Figures 11 and 12, respectively. Tables 1 and

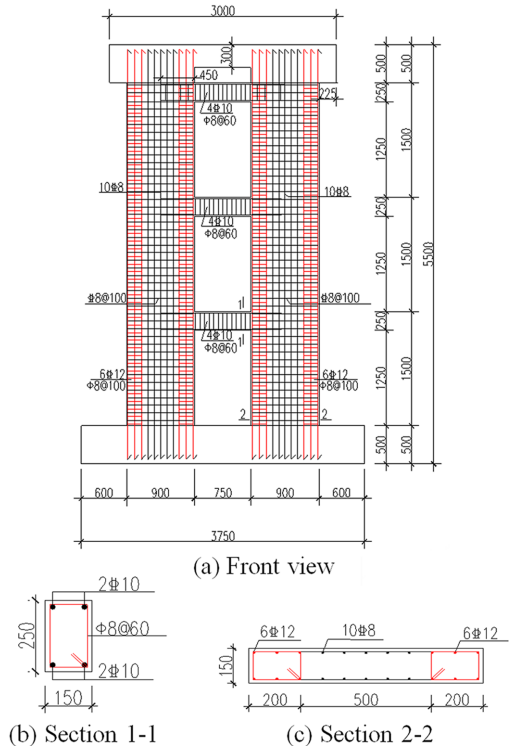


Figure 11. Dimensions and steel reinforcement of CW.

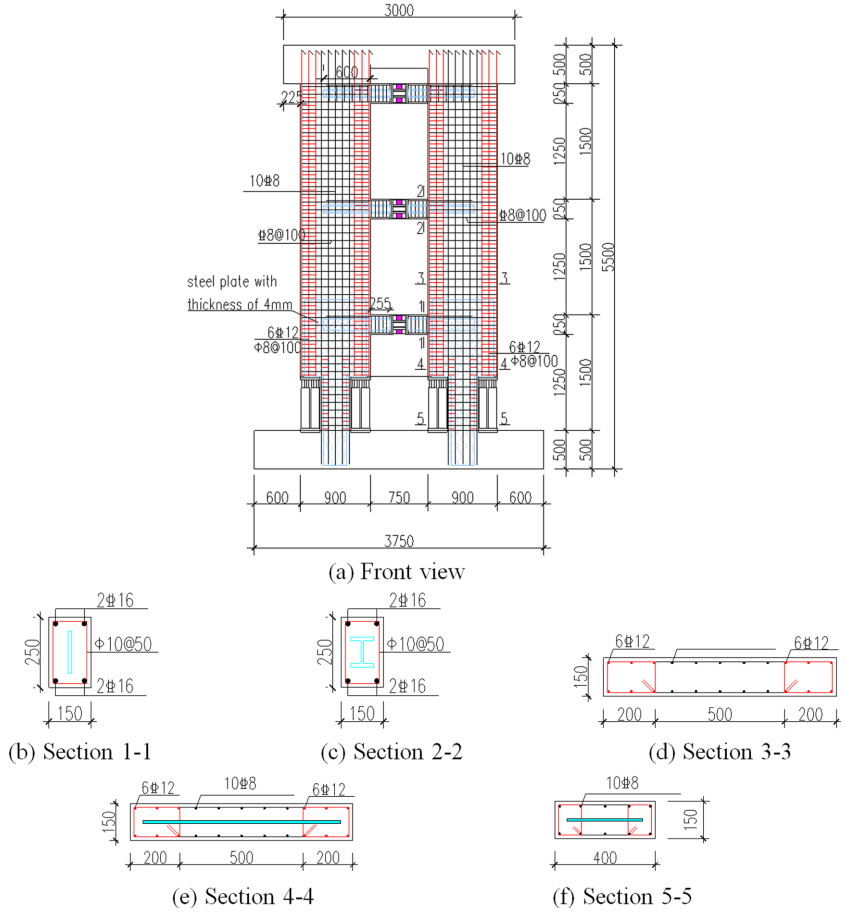


Figure 12. Dimensions and steel reinforcement of NW

Table 1. Dimensions of RCC

Specimens number	Length of replaceable part (mm)	Height of replaceable part (mm)	External diameter of steel tube (mm)	Thickness of steel tube (mm)	Width of inner core (mm)	Thickness of inner core (mm)
NW	250	685	108	6	40	16

Table 2. Dimensions of combined damper

Length (mm)	Web thickness (mm)	Web height (mm)	Number of web	Flange width (mm)	Flange thickness (mm)	Dimensions of VE damper (mm)
160	6	48	1	60	14	8×60×70

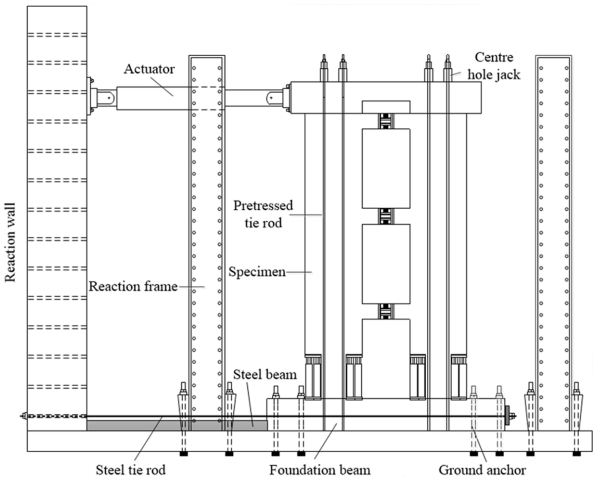


Figure 13. Test setup.

2 illustrate the dimensions of RCC and combined damper.

The design axial compressive load ratio was 0.24. The axial load was applied to specimens by 8 prestressed rods. The lateral load was applied at the top, controlled by the force before the specimen yielded and then by the displacement until failure.

Figure 14 shows the failure mode of specimens. In specimen CW, the coupling beams were damaged seriously. At the bottom of wall piers the concrete crushed and spalled, and the longitudinal reinforcement buckled. However, in specimen NW, the damage concentrated on replaceable components. The combined dampers were damaged in the form of the fracture of the weld between the web and the end plate and the failure of bolt connection of VE damper. Non-replaceable parts of specimen NW mainly remain roughly elastic. Figure 15 shows the lateral force-top displacement hysteretic curves. Compared with specimen CW, the maximum load of specimen NW (595.5 kN) was 1.48 times that of Specimen CW (402.9 kN). The initial stiffness of specimen NW was close to that of specimen CW.

5. Case study

5.1. Analytical model

To verify the performance of the new type of shear wall under the wind and the earthquake, two 32-story frame-tube tall building structures, including one conventional structure and one new structure with new type of shear wall, were designed and analyzed using software Perform-

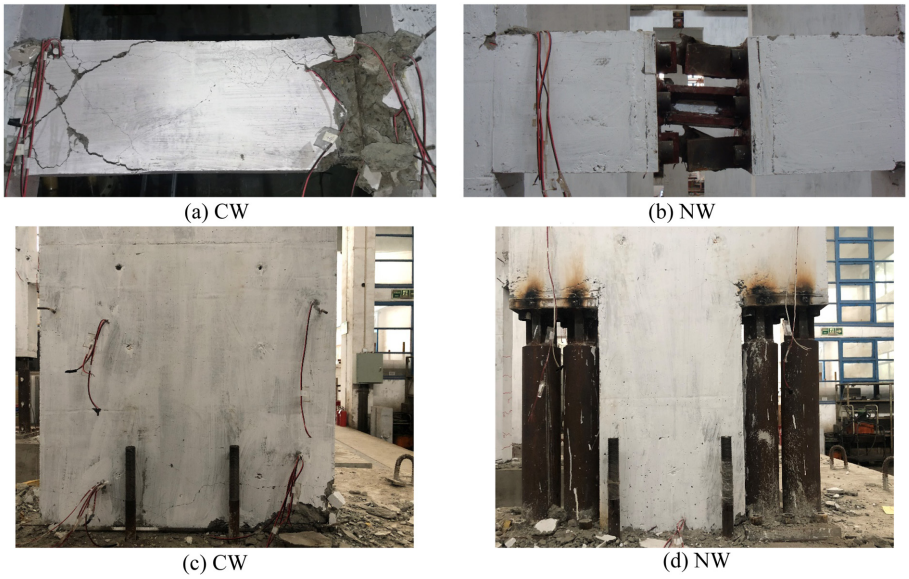
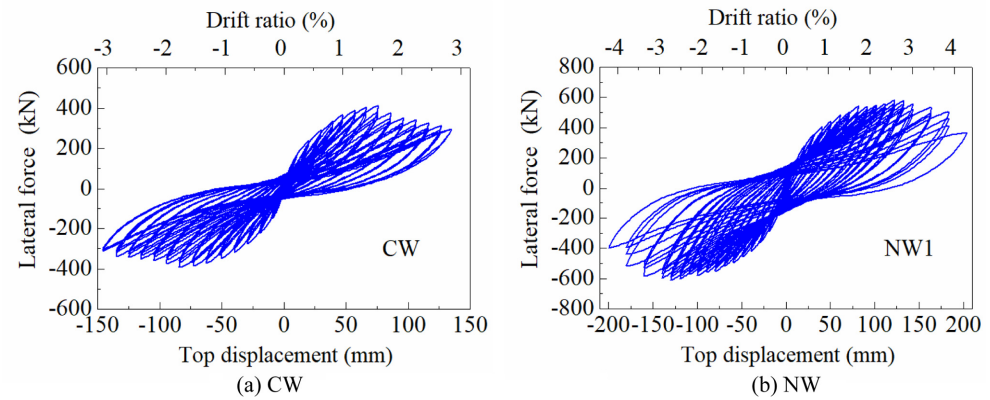
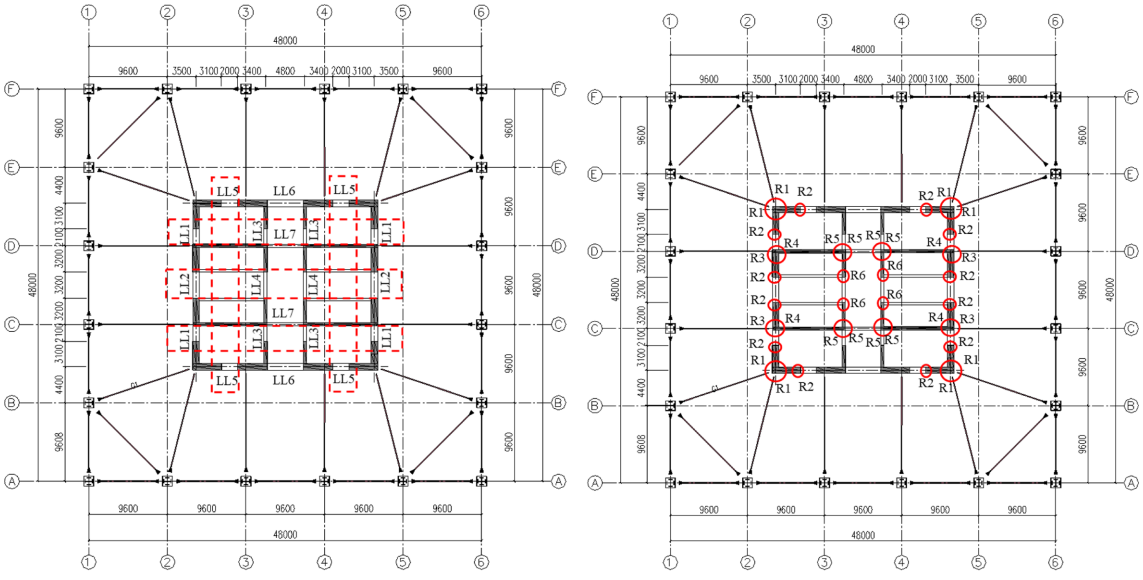


Figure 14. Final failure mode.



(a) CW (b) NW

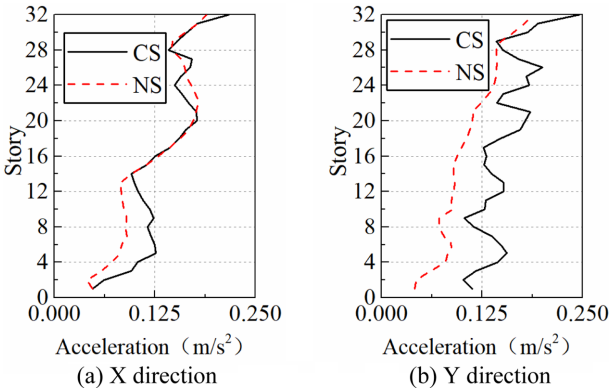
Figure 15. Lateral force-top displacement hysteretic curves.



(a) Replaceable coupling beams (b) RCCs

Figure 16. Layout of replaceable components.

3D. The details of the structures and the numerical models can refer to the reference (Li *et al.* 2019). Replaceable coupling beams were installed in the 2nd to 20th floor, and RCCs were installed in the 1st floor. The plan layout of the replaceable components is shown in Figure 16.



(a) X direction (b) Y direction

Figure 17. Comparison of peak acceleration.

5.2. Responses under the wind

Figure 17 shows the peak accelerations at each story of two structures under the wind with 10-year return period. Compared with the conventional structure named as CS, the peak acceleration at the top of the new type of

Table 3. Information of seismic inputs

Order	Name	Information
1	NGA55	San Fernando, 1971, Buena Vista-Taft
2	NGA67	San Fernando, 1971, Isabella Dam (Aux Abut)
3	NGA75	San Fernando, 1971, Maricopa Array#2
4	NGA813	Loma Prieta, 1989, Yerba Buena Island
5	NGA1833	Hector Mine, 1999, Snow Creek
6	Wave1	Artificial wave 1
7	Wave2	Artificial wave 2

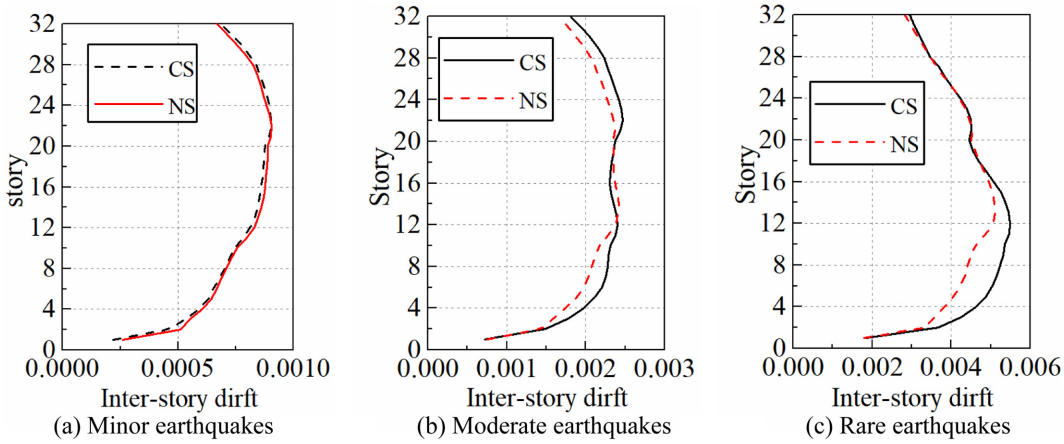


Figure 18. Inter-story drift of structures in Y direction.

Table 4. Averaged ratio of energy dissipated by each type of component under 7 seismic waves (unit: %)

	Moderate earthquakes				Rare earthquakes			
	Coupling beams	Combined dampers	Walls	RCCs	Coupling beams	Combined dampers	Walls	RCCs
CS	48.6	-	49.9	-	72.3	-	24.8	-
NS	11.5	54.3	29.9	3.2	25.2	51.7	16.1	5.1
Difference	–76.3	-	–40.0	-	–65.1	-	–35.1	-

structure named as NS in X and Y directions reduced 12.9% and 23.6%, respectively.

5.3. Responses under the earthquake

Seven sets of earthquake waves were used as seismic inputs. Table 3 lists the information of ground motions. The earthquake intensity is 8 by Chinese standard. The corresponding peak ground acceleration for the minor, moderate, and rare earthquake is 70 gal, 200 gal and 400 gal, respectively.

Figure 18 shows the average of the maximum inter-story drifts in Y direction under different intensity levels of earthquake. Under minor earthquakes, inter-story drift of NS was similar to that of CS. Under moderate earthquakes and rare earthquakes, the replaceable components yielded and dissipated large amount of energy, and the maximum inter-story drift of NS reduced significantly.

Table 4 shows the ratio of the energy dissipated by different type of components to the total energy for two structures. Compared with CS, most of the energy in NS was dissipated by replaceable components, and the energy dissipated by the non-replaceable parts was reduced significantly so that the damage to NS mainly concentrated on replaceable components and the other parts were well protected during the moderate and rare earthquakes.

Conclusions

In this study a new type of earthquake resilient RC shear wall structure was proposed. Based on the test results and case study, the following conclusions are drawn:

The tests on replaceable component demonstrate that the combined damper and RCC exhibit very stable hysteretic behavior, and have the advantages of high capacity of deformation and energy dissipation.

In the earthquake resilient shear walls under the strong earthquake, the damage mainly concentrates on replaceable components, and the non-replaceable parts are well protected.

Compared with conventional structure, the acceleration response of the new type of structure is reduced effectively under the wind.

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