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STUDY ON THE SHEAR WALL STRUCTURE WITH COMBINED FORM OF REPLACEABLE COMPONENTS

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Abstract. *Earthquake resilient structure is an innovative type of structure developed for the purpose to restore the structure immediately after strong earthquakes. The structures with replaceable components is a kind of earthquake resilient structure. Based on the previous studies, combined form of the replaceable devices were applied in the coupled shear wall in this paper. Replaceable coupling beam and replaceable wall foot were used to concentrate the possible damage in the coupled shear wall. The numerical simulation models were verified by the test results of shear walls with each type of the replaceable devices. Then the shear wall model with the replaceable coupling beam and the replaceable wall foot together was studied in detail through parameter analysis. The results show that the influence of the shear wall capacity is small, and the variable parameters have some influence on the stiffness.*

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1 INTRODUCTION

The structure design method to prevent the structural collapse under earthquakes is necessary. However, the damage after earthquakes is hard to repair or the repair time would be so long that to disturb the normal operation of the building. Earthquake resilient structure [1] is an innovative type of structure developed for the purpose to restore the structure immediately after strong earthquakes, in a way that little repair is needed and the repair time is very short. The earthquake resilient structural system includes the self-centering structures, rocking structures, the structures with replaceable components and so on. Previous research proved the structure with replaceable components could achieve the goal of quick repair. When parts of the structural component are replaced by replaceable devices, the structural component will act as a structural "fuse". The damage concentrates in the replaceable device during an earthquake, and the damaged part could be replaced conveniently after the earthquake, which could have less repair time than the traditional structure.

The structure with replaceable components was first introduced for steel structures. A replaceable "fuse" device in steel coupling beam was proposed by Fortney [2]. Cyclic tests of the specimens that consisted of two wall piers and connected by a single coupling beam were carried out. An excellent energy dissipation capacity and reduced damage was found in the steel coupling beam with central fuse [3,4]. A type of replaceable link was bolted to the tower shafts of east span of the new San Francisco-Oakland Bay Bridge [5]. Cyclic tests of the replaceable links excellent plastic deformation capabilities with easy replacement after the test [6]. Christopoulos developed two types of nonlinear replaceable links for steel moment resisting frames [7] and eccentrically braced steel frames [8]. Full-scale cyclic tests of steel beam-to-column subassemblies with replaceable links and the steel eccentric braced frame with replaceable links were carried out. The test results showed that the replaceable links exhibited great energy dissipation and higher rotation.

As for the reinforced concrete (RC) shear wall structures, the structure with replaceable coupling beams and the structure with replaceable wall foots were proposed by the authors[1, 9,10]. The replaceable coupling beam consists of the central replaceable device and the non-yield connecting beams at the two ends. The replaceable wall foot is a compression-tension rubber bearing replacing the RC wall foot. The replaceable device is allowed to undergo plastic deformation and the end-plate bolt connection is used to implement replacement of the damaged device after strong earthquakes. Three coupled shear walls with replaceable coupling beams and one shear wall with conventional coupling beams were tested under static cyclic loading .The results showed that the conventional RC coupling beams experienced failure at beam ends whereas the plastic deformation of the replaceable coupling beam mainly concentrated on the replaceable device. Four innovative shear walls with replaceable wall foots and one conventional shear wall were also tested under cyclic loads. The severe damage at the conventional shear wall foots was observed whereas the damage was concentrated in the replaceable foots of the innovative shear walls. The replacement could be easily implemented owing to the bolt connection between the replaceable part and the remaining part.

It is noted that previous research focused on the structure with one type of the replaceable devices. To further investigate the combined form of the replaceable coupling beam and the replaceable wall foot, the numerical study was conducted in this paper. First, the numerical simulations of the shear walls with one type of the replaceable devices were carried out by comparison with the tested results. Then the shear wall with the replaceable coupling beam and the replaceable wall foot together was studied in detail.

2 FINETE ELEMENT STUDY

The object-oriented, open source software OpenSees is used to develop nonlinear finite element model of the shear walls. Cyclic Softened Membrane Model (CSMM) is used to simulate the RC wall panel. The boundary zone is modeled by displacement-based beam-column element with fiber sections. The numerical models of the replaceable devices are discussed as follows.

2.1 Replaceable coupling beam modeling

Figure 1 shows the replaceable coupling beam proposed by authors. It consists of the non-yield parts at the two sides and the yield part at the center. It is expected that the yield part undergoes shear yielding and the non-yield parts remain elastic under strong earthquakes. The non-yield part was conventional SRC beam, the RC beam embedded with the shape steel. The yield part was the replaceable device made of low yielding point steel. The end-plate bolt connection was used to implement the replacement of the yield part easily after strong earthquakes.

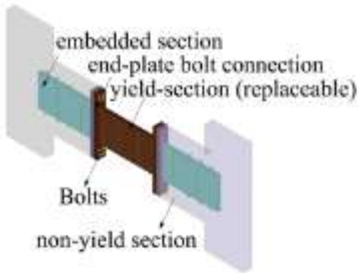


Figure 1. Overview of the replaceable coupling beam

To simulate the shear force-displacement relationship of the replaceable device, a truss element with the Hysteretic material was used. The SRC beam was modeled by beam-column element with fiber section. Parallel truss elements were used to transfer the axial force of the replaceable device. The numerical model is shown in Figure 2.

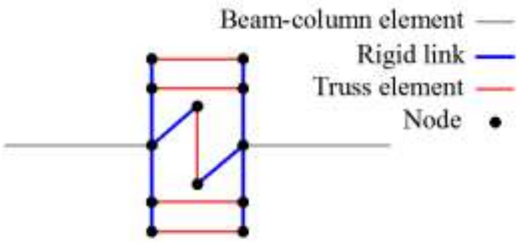


Figure 2. Numerical model of the replaceable coupling beam

2.2 Replaceable wall foot modeling

The proposed replaceable wall foot is illustrated in Figure 3. The central part was the laminated rubber with steel shims in-between. On each side of the rubber layers, a steel plate made of low yielding point steel was settled. The laminated rubber is supposed to resist most of the compression force and the tension force is mainly resisted by the steel plates. A strong connection plate was used to make the rubber layers and steel plates work together. Replacement was also achieved by the end-plate bolts.

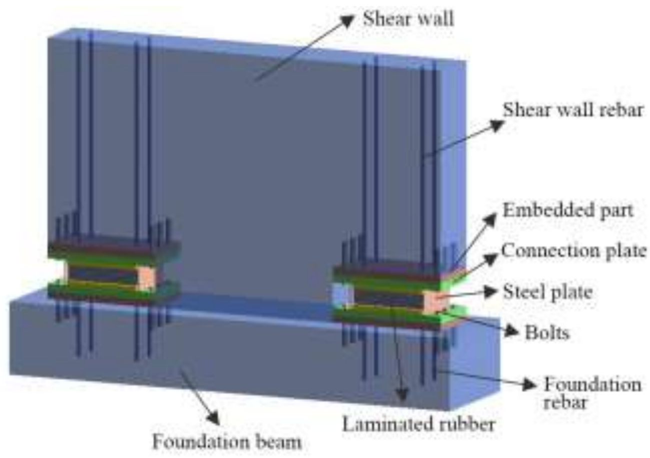


Figure 3. Overview of the replaceable wall foot

To simplify the behavior of the replaceable wall foot, beam-column element with fiber section was used, as shown in Figure 4. Hysterical material was adopted to simulate the behavior of the steel plate and the laminated rubber layers was represented by Elastic-No tension material. Previous research [1] suggests a calculation method of the key points of the skeleton curve for the proposed replaceable wall foot. As for the simulation, the tension strength of the laminated rubber layer was considered in the hysterical material, so no tension strength was included in Elastic-No tension material.

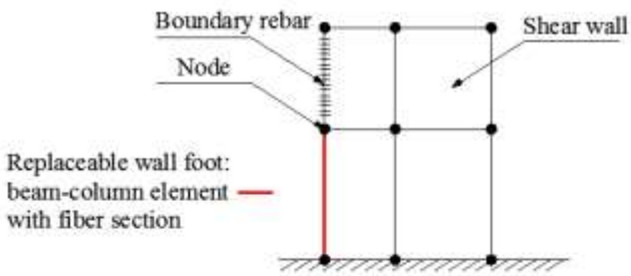
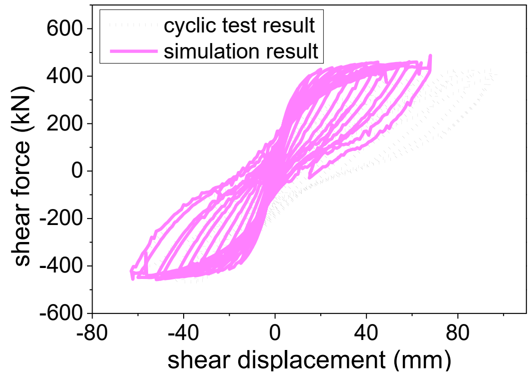


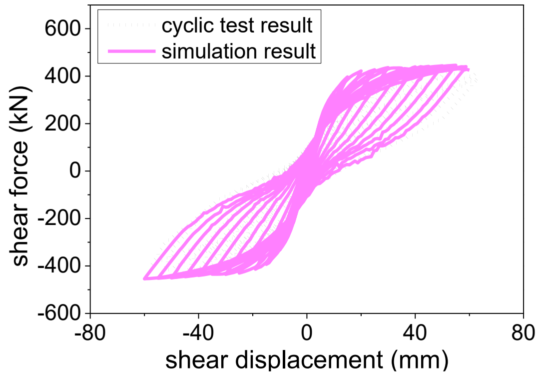
Figure 4. Numerical model of the replaceable wall foot

2.3 Model verification

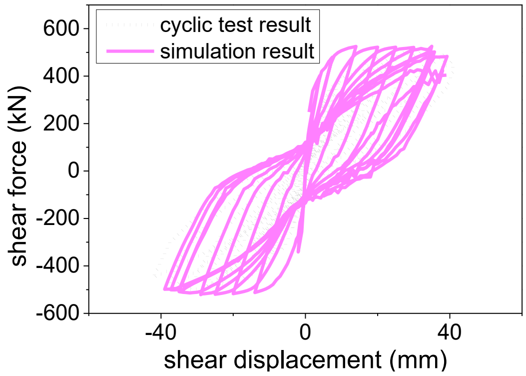
The finite model results are compared with the test results to verify the modeling approach discussed above. Specimen CSW and F1SW tested by Chen[9] were modeled to validate the simulation of replaceable coupling beam. Specimen SW-0 and NSW1-2[1] were created to verify the modeling of replaceable wall foot. The axial force was applied to the model as nodal force and a multi-point constraint was placed at the top nodes to apply the horizontal displacement loads. Figure 5 compares the top displacement-base shear hysteretic curves of the experimental and numerical results. The model properly predicted the behavior of the conventional shear wall and the shear wall with replaceable devices. Figure 6(a) is the numerical hysterical behavior of the replaceable device in coupling beam, and the comparison of the test and simulation behavior of the replaceable wall foot is shown in Figure 6(b). The simulation results agree well with the experimental results, which proves a proper simulation method of the replaceable devices.



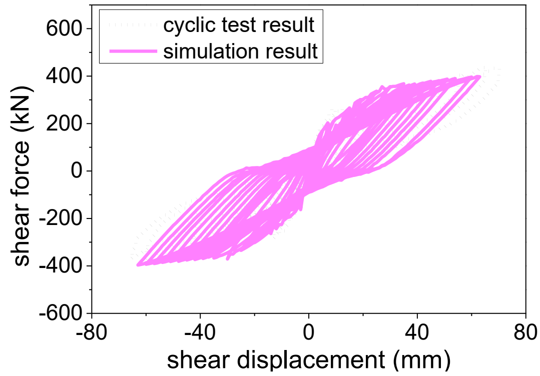
(a) CSW



(b) F1SW

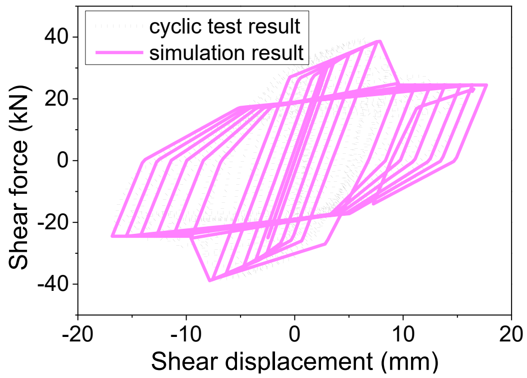


(c) SW-0

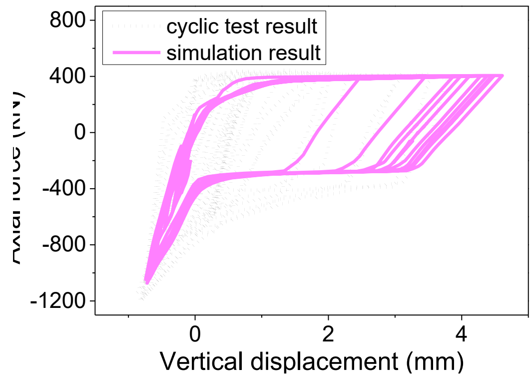


(d) NSW1-2

Figure 5. Top displacement-base shear hysteretic curves



(a) Replaceable device in F1SW



(b) Replaceable wall foot in NSW1-2

Figure 6. Numerical hysterical behavior of the replaceable devices

3 SHEAR WALL WITH COMBINED FORM OF REPLACABLE DEVICES

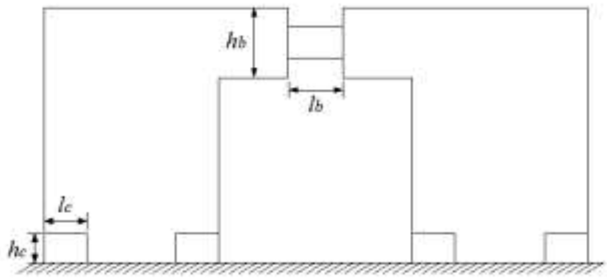


Figure 7. Dimension mark of the combined replaceable devices in shear wall

According to the design method proposed by the authors [9,11], shear wall with combined form of the replaceable coupling beam and the replaceable wall foot was created. As shown in Figure 7, the height of the non-yield connection beam h_b and the span of the replaceable device l_b are defined according to the strength and stiffness equivalence of the replaceable coupling beam to the conventional coupling beam [12]. To concentrate the plastic damage, the height of the replaceable wall foot h_c should be larger than the length of the plastic hinges [13].The width of the replaceable wall foot l_c was determined by the region where the compression strain of the concrete exceeds ε_x, in order to avoid the concrete crush. The minimal height and width of the replaceable foot are calculated as follows:

$$h_c \geq 0.2h_w + 0.044H \tag{1}$$

$$l_c \geq 1.5(1-\frac{\varepsilon_x}{\varepsilon_{c,\max}})\xi h_0 = 1.5(1-\frac{\varepsilon_x h_p}{\theta_u \xi h_0})\xi h_0 \tag{2}$$

where h_w, H are the cross-section depth and effective height of the shear wall respectively [14], $\varepsilon_{c,\max}$ is the maximum compressive strain at the extreme compression edge, which equals the ultimate curvature plus the equivalent compression zone height ξh_0 of the bottom section of the shear wall. The ultimate curvature of the section is defined as the ratio of the maximum story drift θ_u to the height of the plastic hinge h_p.

In order to further study the parameter influence to the performance of shear wall with replaceable devices, a parameter study was conducted. A base model for the parameter analysis was chosen as shown in Figure 8. The influence of four parameters was analyzed by changing one parameter and keeping the other three unchanged at a time.

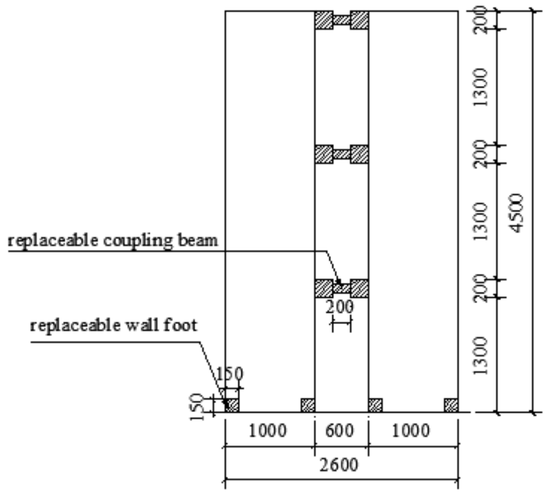


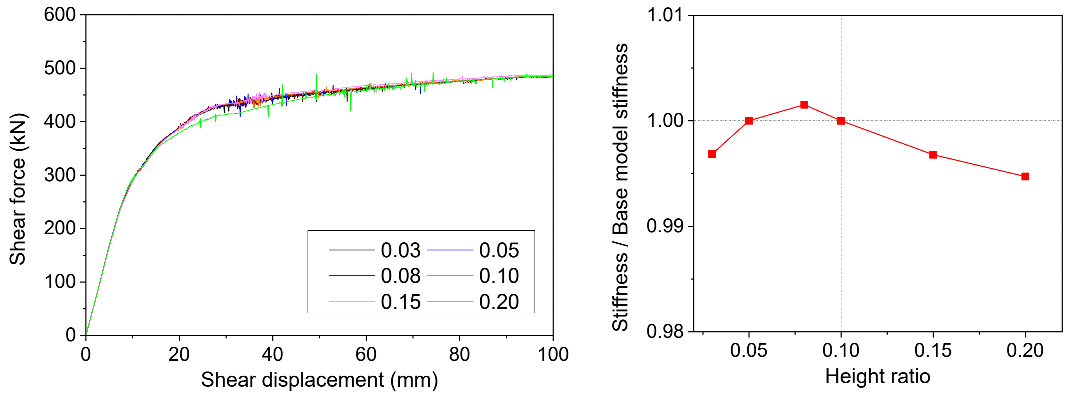
Figure 8. The base model for parameter analysis

3.1 Height of the replaceable wall foot

To investigate the influence of height of the replaceable wall foot h_c, several numerical models with different height ratio were analyzed. The height ratio R_h was defined as Equation (3):

$$R_h = h_c / H \tag{3}$$

where h_c, H are height of the replaceable wall foot and the effective height of the shear wall respectively. Figure 9 shows the comparison of load capacity and stiffness of the numerical models with different height ratio. The shear wall capacities are almost the same with different wall foot height. With the increasing of the wall foot height, the initial stiffness increases first and then decrease, which indicates a proper height ratio range is 0.05~0.10.



(a) Load-displacement curves (b) Comparison of initial stiffness

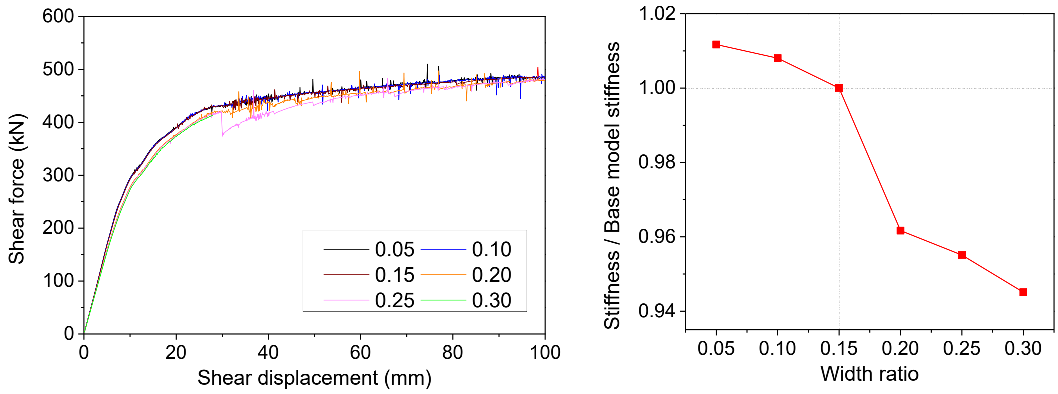
Figure 9. Influence of the wall foot height

3.2 Width of the replaceable wall foot

The width ratio R_w was defined by Equation (4) and several numerical models with different width ratio R_w were used to investigate the influence of width of the replaceable wall foot:

$$R_w = l_c / h_w \tag{4}$$

where l_c, h_w are the width of the replaceable wall foot and the cross-section depth of the shear wall respectively. As shown in Figure 10, the shear wall capacities are almost the same but the initial stiffness decreases with the increase of wall foot width.

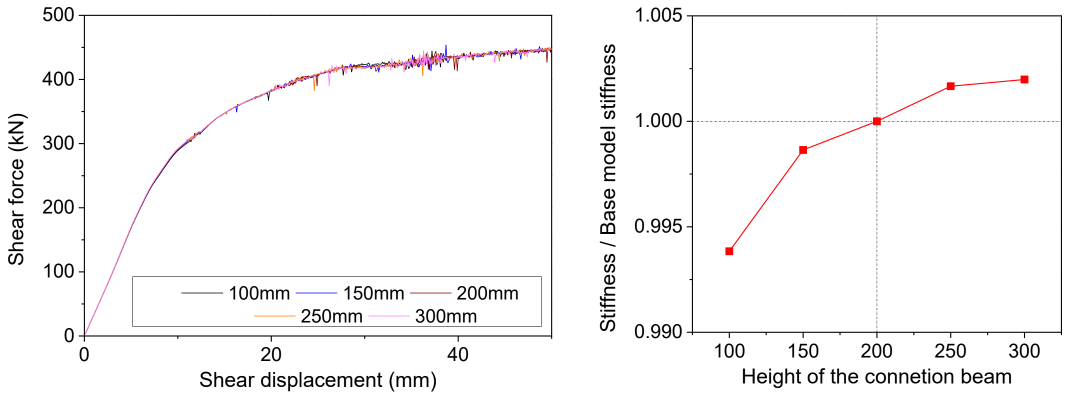


(a) Load-displacement curves (b) Comparison of initial stiffness

Figure 10. Influence of the wall foot width

3.3 Height of the non-yield connection beam

Figure 11 shows load-displacement curves with different height of non-yield connection beams and the comparison of initial stiffness. The influence to the shear wall capacity is small because the capacity is determined by the shear capacity of the replaceable device, not the connection beam. The initial stiffness results show that the stiffness increases with the larger connection beam height, but the difference is not so obvious because the coupling beam height is not so deep and the stiffness contribution to the shear wall is small. Supposing a much deep coupling, the stiffness deviation due to connection height change would be larger.

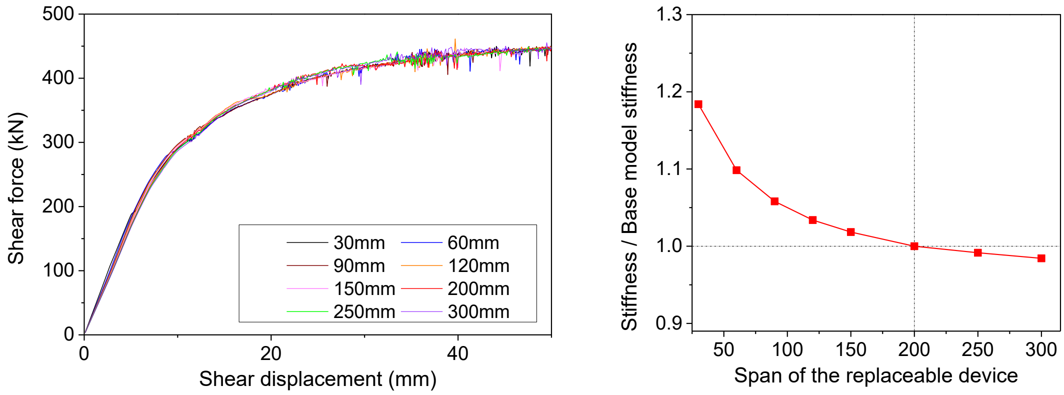


(a) Load-displacement curves (b) Comparison of initial stiffness

Figure 11. Influence of the connection beam height

3.4 Span of the replaceable device

The influence of the replaceable device span is shown in Figure 12. The shear wall capacities are similar but the difference is larger than that of the connection beam height. The initial stiffness gets larger when the span of the replaceable device gets smaller, and the increase becomes higher with the small span.



(a) Load-displacement curves (b) Comparison of initial stiffness

Figure 12. Influence of the replaceable device span

4 CONCLUSIONS

- To make the damage replaceable and the structure earthquake resilient, replaceable devices should be located in all area which could be easily damaged. For coupled shear wall, coupling beam and wall foot are parts which are easy to be damaged. So based on the previous study, combined form of the replaceable devices were applied in the coupled shear wall in this paper. Numerical simulation was carried out in OpenSees and parameter analysis was conducted based on the verified finite element models.
- Truss element with the hysteretic material could be used to simulate the replaceable device in coupling beam and the behavior of the replaceable wall foot could be modelled by beam-column element with fiber section. Simulation results of the replaceable devices and the shear wall agree well with the experimental results, which proves a proper simulation method.
- The height of the non-yield connection beam, the span of the replaceable device, the height and width of the replaceable wall foot are variable parameters for the coupled shear wall with combined form of replaceable components. The parameter study shows that the shear wall capacity is little influenced by the variable parameters of each replaceable devices but the stiffness are different. With the increasing of the wall foot height, the initial stiffness increases first and then decrease, and a proper wall foot height ratio range of 0.05~0.10 is proposed. The initial stiffness decreases with the increase of wall foot width and the decrease of connection beam height. When the span of the replaceable device gets smaller, the initial stiffness increases, and the increase gets faster in the small range.

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