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Structural Shear Wall Systems with Metal Energy Dissipation Mechanism

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Abstract

Shear wall structures have been widely used in high-rise buildings during the past decades, mainly due to their good overall performance, large lateral stiffness, and high load-carrying capacity. However, traditional reinforced concrete wall structures are prone to brittle failure under seismic actions. In order to improve the seismic behavior of traditional shear walls, this paper presents three different metal energy-dissipation shear wall systems, including coupled shear wall with energy-dissipating steel link beams, frame with buckling-restrained steel plate shear wall structure, and coupled shear wall with buckling-restrained steel plate shear wall. Constructional details, experimental studies, and calculation analyses are also introduced in this paper.

Keywords: shear wall; energy-dissipation; coupled shear wall with energy-dissipating steel link beam; frame with buckling-restrained steel plate shear wall structure; coupled shear wall with buckling-restrained steel link plate

1. Introduction

Generally, high-rise buildings are likely to experience extraordinary seismic actions and wind loads; consequently, stiffness design is the primary issue in the structure design. Due to extraordinary overall structural integrity, large lateral stiffness and high load-carrying capacity, reinforced concrete shear walls are widely used in high-rise structures [1,2]. As is known, based on different height-to-depth ratio, the cantilever shear walls can be categorized as slender walls or squat walls. The slender wall is essentially a cantilever, which will experience the largest bending moments at the bottom. Its most possible and desirable failure mode is flexural failure, which exhibits sufficient ductility. However, under some circumstances, such as poor details and unexpectedly rare earthquakes, brittle failure may occur. For example, under extremely large earthquakes, boundary elements of the bottom wall piers are likely to suffer huge tensile forces, which results in the yielding even fracture of reinforcing rebar. Under reversed loading, propagation of cracks may also lead to sudden failure, exhibiting limited ductility, as seen in Fig. 1(a). Besides, under large axial forces, thin wall elements also tend to have a compression out-of-plane buckling failure (shown in Fig. 1(b)). On the other hand, for the squat walls, pure shear failure is always their main failure mode under seismic loads, as seen in Fig. 1(c), which always exhibit disappointing energy-dissipation capacity and seismic performance.

As such, from the perspective of structural design against static and dynamic forces, structures should not only have sufficient stiffness and load-carrying capacity, but also have excellent ability to dissipate and consume the input dynamic energy to avoid the above-mentioned brittle fail-



(a) shear-compression failure



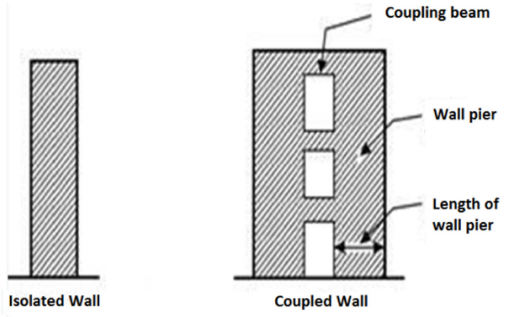
(b) buckling failure



(c) shear failure

Figure 1. Typical damage of traditional shear walls.

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(a) Cantilever shear wall (b) Coupled shear wall

Figure 2. Coupled shear walls.

ure. Once the structure is able to effectively dissipate the energy, such as through plastic deformation, the ductility of structure is increased, which will assist to resist the earthquake impact.

In high-rise buildings, shear walls usually have door or windows penetration to accommodate the architectural functions. Consequently, coupling beams are formed to connect the wall piers at intervals through the structural height, which is referred to be coupled shear walls, as demonstrated in Fig. 2(b). Compared to the cantilever shear walls, their stiffness and load- carrying capacity may be lower. However, their ductility capacity can be considerably increased because of the excellent ductility capacity of coupling beams. Meanwhile, coupling beams are also able to dissipate the earthquake-induced energy through plastic deformation, so that the seismic actions on structures can be significantly reduced [1,3].

Although this strategy to increase the seismic performance of high-rise buildings is quite straight-forward, unfortunately, the hysteretic behavior of concrete coupling beams is always insufficient and undesirable to fulfil this seismic philosophy. It is known that concrete material features the brittle behavior and poor energy dissipation capacity, so cracks and brittle failure (as seen in Fig. 3) [4], poor energy dissipation capacity and lack of sufficient deformation ability (as seen in Fig. 4) [4] is commonly seen in the damage to concrete coupling beams. Different from concrete material, steel material is characteristic of extraordinary ductility and energy dissipation capacity. Therefore, steel material is encouraged in the application of energy-dissipating elements in structures.

This research paper proposes three types of structural wall systems with metal energy dissipation devices, including coupled shear walls with damping steel link beams, frame with buckling-restrained steel plate shear wall and coupled shear walls with buckling-restrained steel plate shear wall, respectively.

Coupled shear walls with energy-dissipating steel link beams substitute traditional concrete coupling beams with the innovative double-step yielding steel coupling beams, aiming to avoid the potential brittle shear failure under shears. One innovative characteristic of the proposed steel coupling beams is that they are able to yield and dissipate the energy through plastic deformation from lower seismic motions such as minor earthquakes. When the quake becomes stronger, their energy dissipation capacity becomes larger. The proposed steel coupling beams are actually

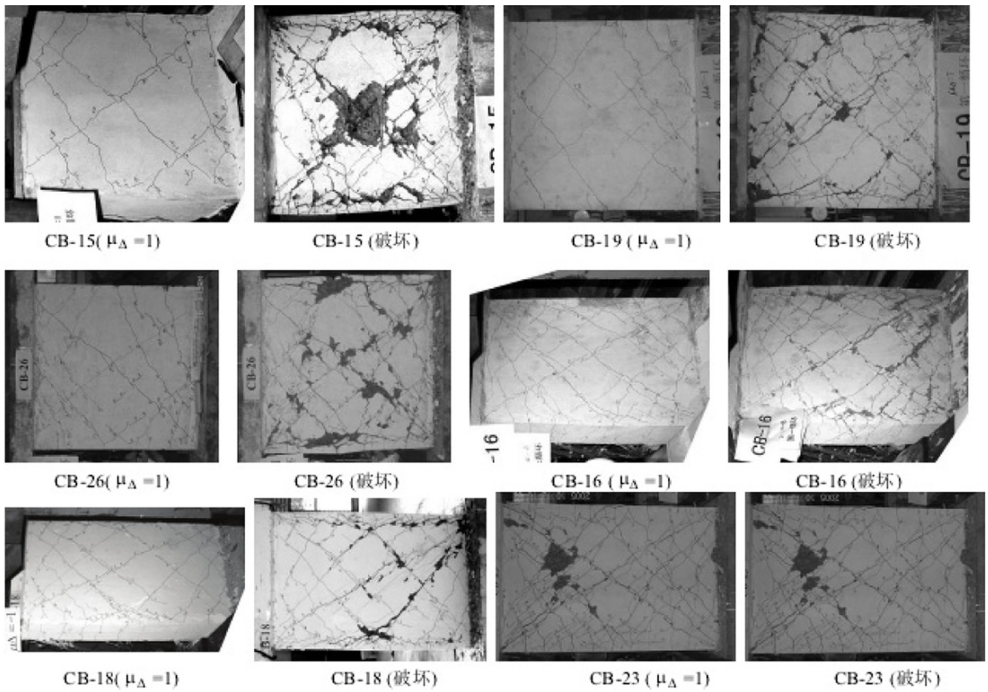


Figure 3. Typical damage of concrete coupling beams (by Tianxiang PI, 2008).

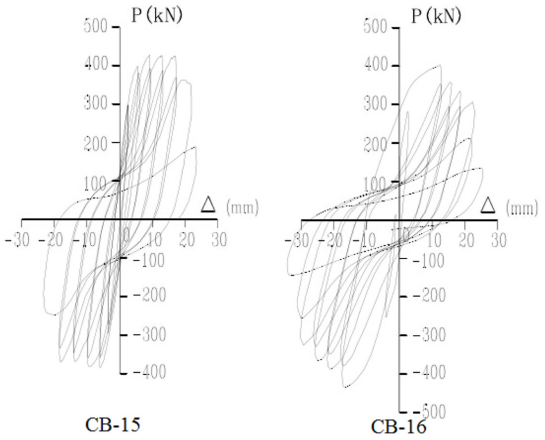


Figure 4. Hysteretic loops of concrete coupling beams (by Tianxiang PI 2008) [4].

composed of two parts, one of which is designed to yield under minor earthquake while the other part remains elastic to maintain considerate coupling effects of coupled shear walls. Consequently, the proposed link elements are capable of providing additional damper and sufficient stiffness under minor earthquakes.

Frames have excellent ductility; however, their lateral stiffness is relatively low. Consequently, in order to enhance the structural stiffness, concrete shear walls are always incorporated in the lateral force resisting system and the frame-shear wall structures are derived. It also should be noted that although the shear walls can increase the overall structural stiffness, their seismic performance is sometimes undesirable. In order to improve their seismic behavior, this research paper proposes a state-of-the-art structural system - frame with buckling-restrained steel plate shear wall structure, in which buckling-restrained steel plate shear wall will help not only increase the stiffness of the structure but also provide superb energy-dissipation capacity and excellent seismic performance.

Shear walls with low aspect ratio tends to fail in shears. To overcome this shortcoming, they can be equipped with buckling-restrained steel link plates. The cantilever shear walls can be turned into two isolated wall piers connected with several buckling restrained steel link plates, which will be located at equal intervals vertically. This kind of innovative structure is referred to be coupled shear wall with buckling-restrained steel link plates. Their primary energy-dissipation elements are the buckling restrained steel link plates, which are inherently excellent in absorb and dissipate input energy, as opposed to the bottom of the walls in cantilever shear walls. Apart from it, another significant advantage of the proposed system is that their lateral stiffness has limited reduction compared to the original cantilever walls. Without doubt, this will benefit the high-rise structures, in which stiffness design dominate the structural design.

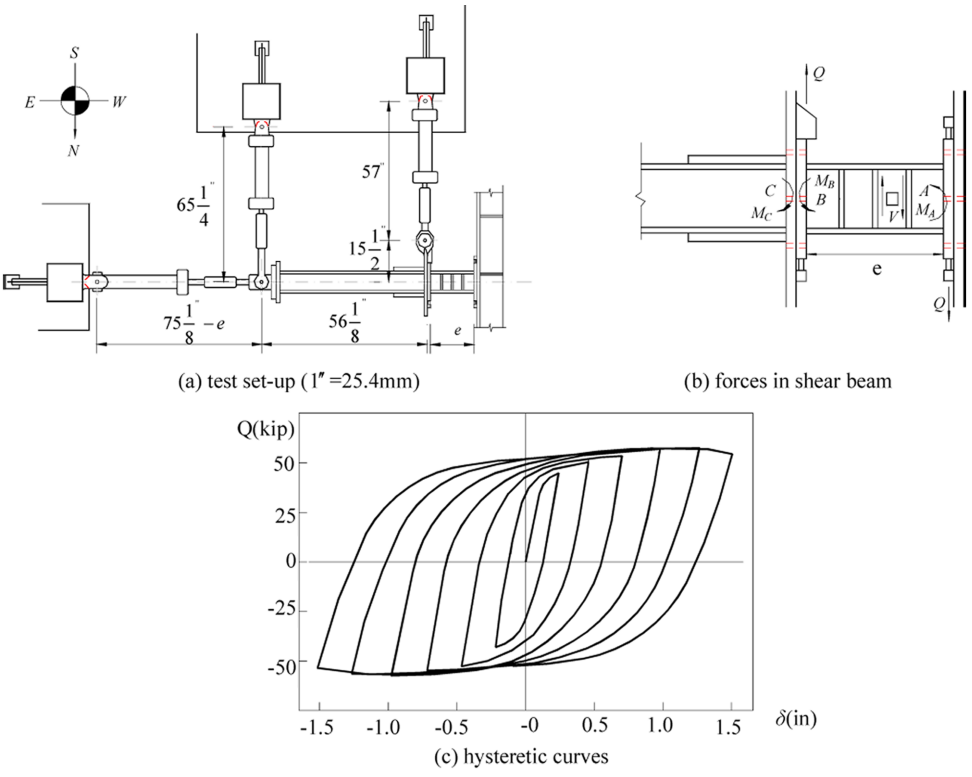


Figure 5. Hysteresis loop of steel link beam (by K. Kasai and E.P. Popov 1986 [5]).

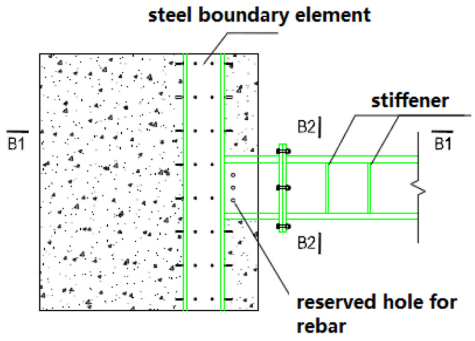


Figure 6. Connection detail between steel link beam and concrete shear wall.

2. Coupled Shear Walls with Damping Steel Link Beams

In order to improve the poor seismic behavior of concrete link beams in coupled wall structures, this research paper proposes to use the steel link beams [5] (as seen in Fig. 5) to improve the structural seismic performance.

In recognition of the different mechanical performance of steel link beams and concrete shear walls, a type of connection detail is proposed to guarantee that steel link beams are able to develop the strength and improve the structural ductility. Embedded steel columns are utilized in the concrete walls for the connection between steel link beams and concrete shear walls (as shown in Fig. 6), whose applicability and effectiveness has been testified by experiments [6].

In order to further increase the seismic performance of steel coupling beams, another energy-dissipation structural element is proposed, which is referred to be double-step yielding steel coupling beams, to reduce the seismic actions under minor earthquakes as well as to maintain a desirable structural stiffness to control the lateral displacement. Since steel material has superb ductility and steel structural members are easily to exhibit excellent and saturated hysteresis loops, their energy-dissipation capacity is always more desirable than that of concrete link beams [7]. The proposed steel link beam is well-designed to possess two yielding points. One Part of the link beam is to yield under design earthquake (minor earthquake), while the other part keep elastic. The configuration is shown in Fig. 7. The energy-dissipation element which will yield under minor earthquakes essentially comprises two parts: elastic zone and inelastic zone, both of which will be incorporated in a double-web I-shaped beam. Under larger earthquakes, such as rare earthquakes, the outside double-web I-shaped beam begins to function and yield. As such, double yielding point will be observed in the load-deformation curve, as seen in Fig. 8.

The application of the proposed double-step yielding steel coupling beams is illustrated in the design of a prototype structure of 18 stories. After the comparison to the design with conventional concrete link beams, it is found that, in minor earthquakes, the proposed double-step yielding steel coupling beams are able to decrease the inter-story drift and story shear by 8% and 15%, respectively,

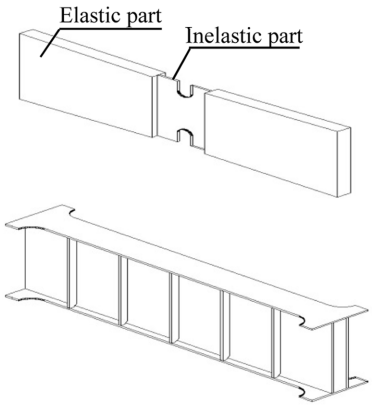


Figure 7. Configuration of double-step yielding steel coupling beams.

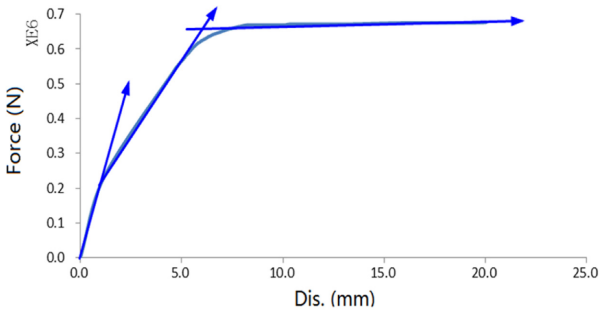


Figure 8. Load-deformation curve.

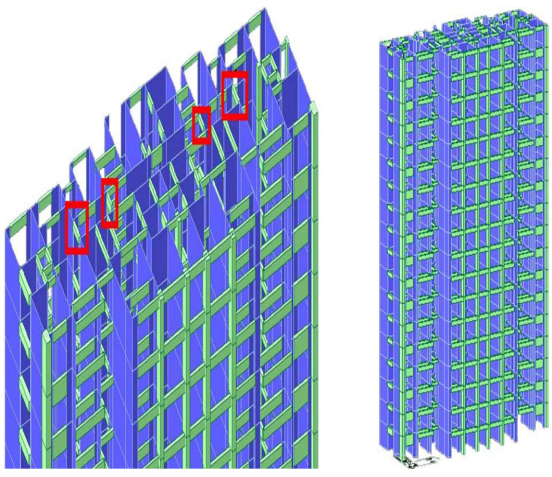
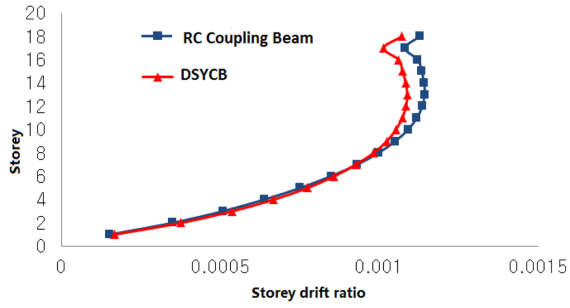
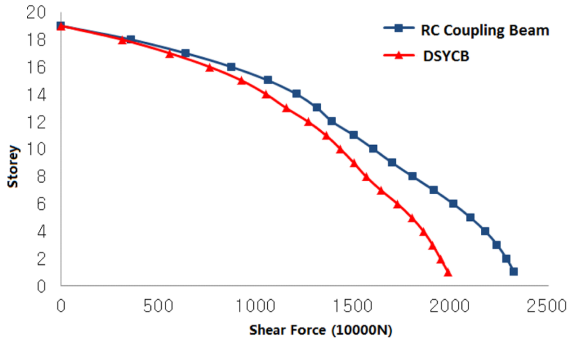


Figure 9. calculation model of prototype structure.



(a) Story drift ratio



(b) Story shear

Figure 10. Comparison between double-step yielding steel coupling beams and conventional concrete link beams under minor earthquakes.

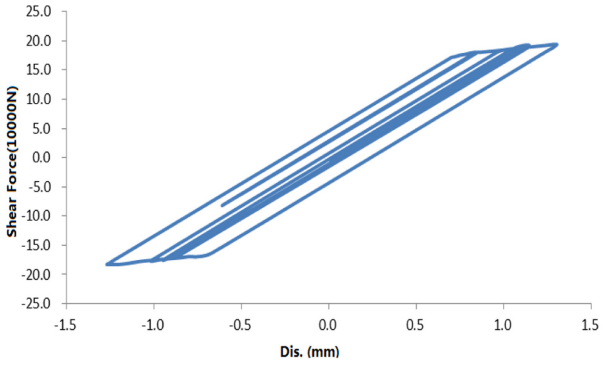
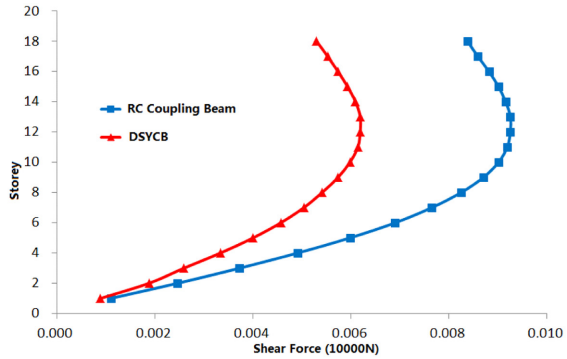
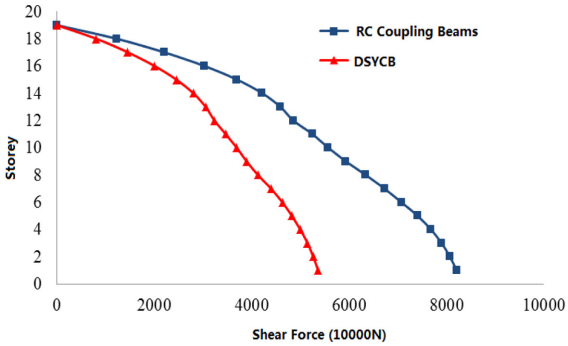


Figure 11. Hysteresis loop under minor earthquake.

as seen in Fig. 10. Meanwhile, the typical hysteresis loop of the proposed steel coupling beam is shown in Fig. 11, which indicates considerate energy-dissipation behavior occurs during the seismic excitation. Under severe earthquake, the proposed structure is able to alleviate the seismic response more significantly, decreasing the inter-story drift ratio and story shear by 40% and 35% respectively (shown in Fig. 12). Fig. 13 indicates the hysteresis loop of the double-step yielding steel coupling beams under severe earthquakes.



(a) Story drift ratio



(b) Story shear

Figure 12. Comparison between double-step yielding steel coupling beams and conventional concrete link beams under severe earthquakes.

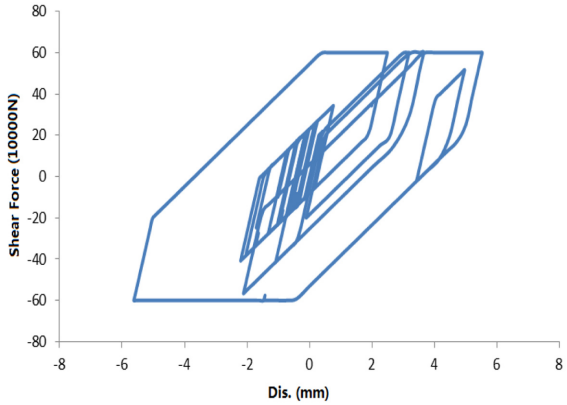


Figure 13. Hysteresis loop under severe earthquake.

3. Frame with Buckling-restrained Steel Plate Shear Wall Structure

Steel plates are able to provide extraordinary in-plane resistance; however, they tend to buckle under in-plane shears, which result in seriously pinched hysteresis loops under cyclic loadings. In order to improve the energy-dissipation capacity of the steel plates and restrain the occur-

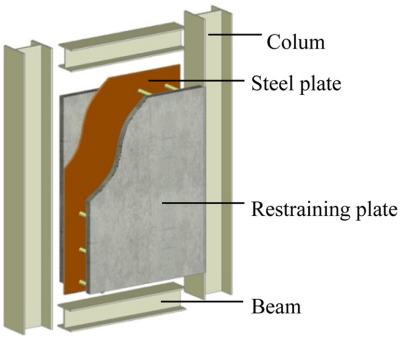


Figure 14. Configuration of buckling-restrained steel plate shear wall.

rence of out-of-plane buckling under shears, buckling-restrained steel plate shear walls are proposed accordingly [8], as shown in Fig. 14. The assembly is mainly composed of a thin steel plate and outer plates on each side which are to restrain the out-of-plane buckling of the infill steel plate. Since the yielding mechanism is through the shear yielding of the infill steel plate and no out-of-buckling will occur, it has excellent capacity in dissipating the input energy.

Regarding the outer plates which are utilized to restrain the infill thin steel plate, they can be made of concrete or steel (steel box plate) provided that they are able to furnish sufficient stiffness and strength. Under the restraint of the outer plates, the infill steel plate is capable of yielding in shears, which guarantee the prominent energy-dissipation capacity of the assembly. Fig. 15 demonstrates the saturated hysteresis loop of buckling-restrained steel plates.

If the buckling restrained steel plates are incorporated in the concrete frames, they are able to increase the structural stiffness, load-carrying capacity and energy-dissipation capacity [9]. In order to solve the connection issue between concrete frames and steel plates, authors proposed a new type of connection as shown in Fig. 16. The thin steel plates of the assemblies will be connected to the steel frames, which are embedded in the concrete frames through fin plates.

With the aim to verify the applicability of the proposed connection details, two sets of two-story single span experiments are conducted under static loading procedure (CSW-1) and cyclic loading procedure (CSW-2), as shown in Fig. 17.

It can be concluded that: (1) the proposed structural system - frame with buckling-restrained steel plate shear wall structure, is characteristic of large stiffness, strength, ductility and excellent energy-dissipation capacity. (2) After yielding of the steel plate shear wall, the structure is able to sustain loads increasingly which imply the sufficient redundancy of the structure. (3) The final failure mode is shear compression failure of the column under compression. (4) The outer cover plate of the assembly is able to

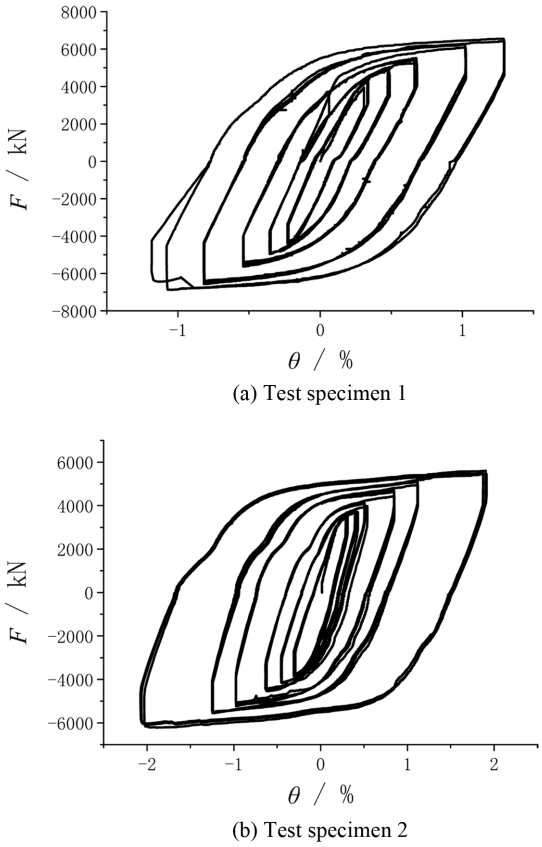


Figure 15. Hysteresis loop of buckling-restrained steel plates.

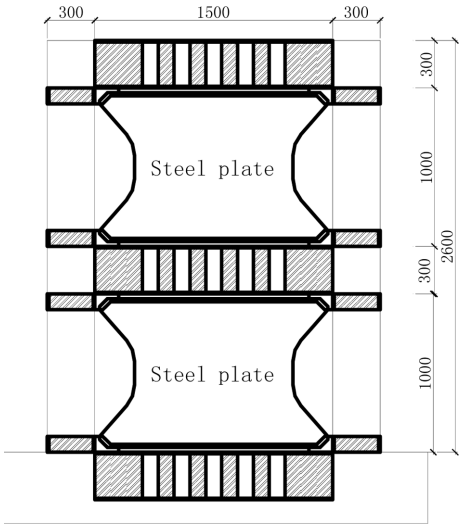


Figure 16. Connection between steel plate and concrete frames.

effectively protect the thin steel plates under loads. No failure of welding or connection part was observed in the



Figure 17. Specimen.

experiment.

Fig. 18 shows the comparison between experimental results and numerical simulation regarding the load-deformation curve of CSW-1 and CSW-2, respectively. It is obviously seen that they are in good agreement and ultimately, the maximum story drift ratio of CSW-1 and CSW-2 can reach to 1/15 and 1/18.6, respectively.

FIg. 19 indicates that the buckling-restrained steel plate is able to significantly increase the initial stiffness, strength as well as the energy-dissipation capacity. For example, the initial stiffness of the first story increases by 2.42 times while that of the second story increases by 4.68 times. Besides, it also indicates in the figure that, the proposed frame with buckling-restrained steel plate shear wall structure also has larger ductility ratio.

Because of the excellent seismic performance of buckling-restrained steel plate shear wall structure, many projects adopted this innovative technique, such as national exhibition and convention center, which has a total area of 1.47 million square meters and top the list of exhibition buildings worldwide as seen in Fig. 20. The installation of the assembly is demonstrated in Fig. 21.

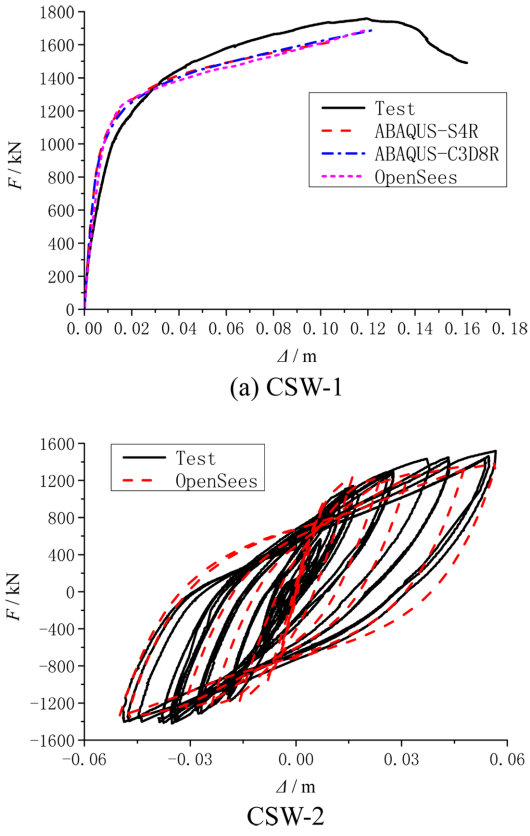


Figure 18. Comparison of load-deformation curve.

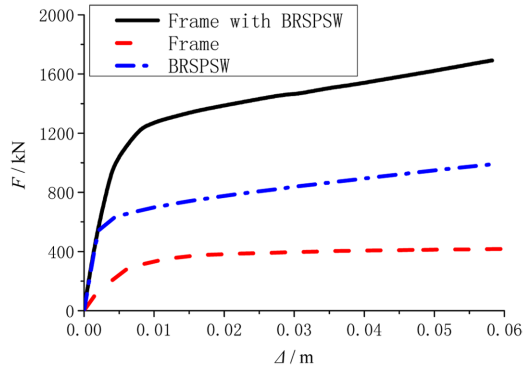


Figure 19. Comparison of load-deformation curve between frame with buckling-restrained steel plate shear wall structure and ordinary concrete frame structure.

3. Coupled Shear Wall with Buckling-Restrained Steel Plate

In order to resolve the problem that long shear walls with low aspect ratio are prone to shear failure, a state-of-the-art energy-dissipating structural system named “coupled shear wall with buckling-restrained steel plate” is herewith proposed, as shown in Fig. 22. The most significant improvement of this system is that the proposed system has dramatically higher elastic stiffness than that of conventional coupled wall systems while maintaining excellent energy- dissipating capacity and desirable ductility as the traditional ones [10].

The comparison between cantilever shear wall and the proposed wall system is shown in Figs. 23 and 24. It can be conclude that the inelastic story drift ratio of the proposed wall system could be significantly reduced compared to that of the cantilever shear wall system.



Figure 20. National exhibition and convention center.



Figure 21. Installation of buckling-restrained steel plate shear wall.

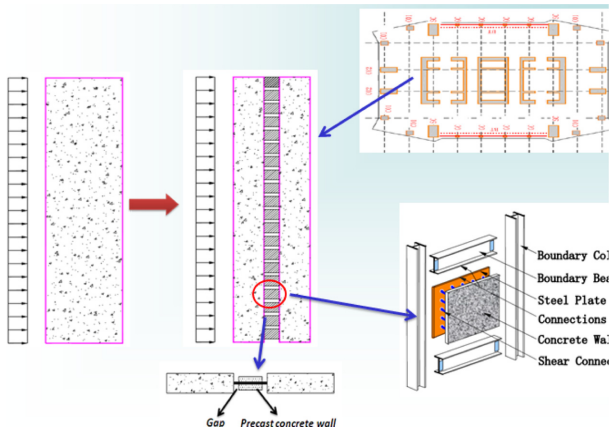


Figure 22. Coupled shear wall with buckling-restrained steel plate.

4. Conclusion

Architectural functions play a more and more important role in modern society, which requires that the structures should not only have the capacity of surviving larger earthquakes but also keep functional after the quake. As such, the buildings which suffer damages should be able to be readily and quickly fully repaired.

Cantilever shear wall structures can furnish large stiffness and high capacity but limited ductility and poor seismic performance sometimes. The best solution to improve their performance is to design it to be a coupled structure, in which steel coupling beams or buckling-restrained steel plate can be engaged as the coupling elements. During earthquakes, the coupling elements are expected to dissipate and absorb the energy to reduce the damage to the wall piers. The innovative wall systems proposed in this research paper are equipped with more advanced coupling elements, which are readily to be fully repaired or replaced after the earthquake when partially and fully damaged in the event.

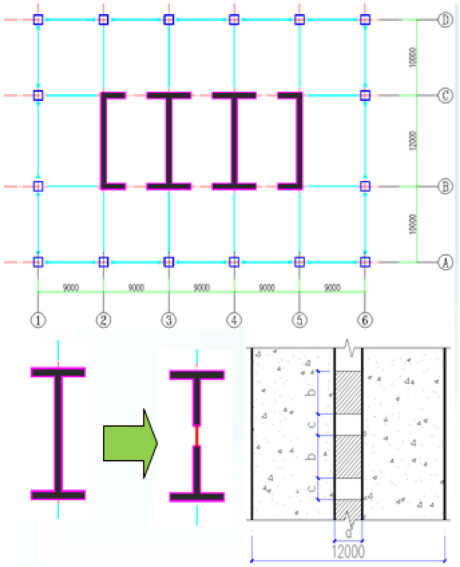


Figure 23. Structural layout.

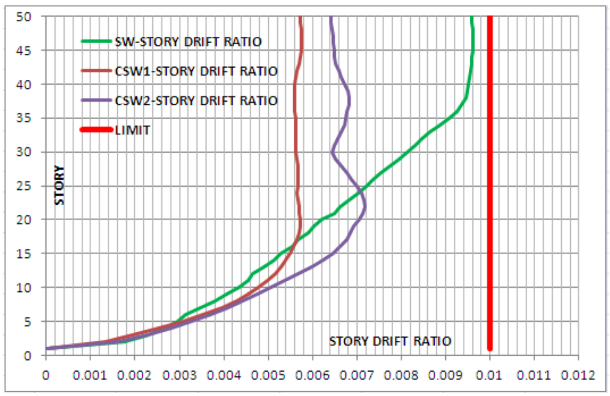


Figure 24. Comparison between cantilever shear wall and the corresponding coupled shear wall with buckling-restrained steel plate.

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