Hysteresis Performance Analysis of Damping Energy Dissipating Corrugated Steel Plate Shear Wall System

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Abstract. As a buckling-resistant component, the corrugated steel shear wall was adopted to restrain the local buckling of the steel plate. The mild steel damper was also added to improve the energy dissipation capacity of the structure, forming a new damping energy-dissipation corrugated steel plate shear wall system (DCSW). In order to study the hysteresis behaviour of DCSW, 5 nonlinear FEMs were established by ABAQUS, with the consideration of corrugated steel plate placement, mild steel dampers arrangement and openings form. Their ultimate bearing capacity, ductility, stiffness and energy dissipation performance were compared and evaluated. The results indicated that the DCSW system had better bearing capacity and energy dissipation capacity. The ultimate bearing capacity of structure with corrugated steel plate shear walls and mild steel dampers increased by 37%~43% and 11.4%~13% respectively, combining using those two elements, their ultimate bearing capacity increased by 52%~56%, and their ductility was also improved significantly.

1. Introduction
The ordinary multi-storey buildings were harder and harder to satisfy the utility requirements with the development of economy and technology in modern society. This provides the possibilities for high-rise and super-high-rise structures to become an alternative solution. And the steel structure, with the advantages of light weight, high strength and good seismic performance, has been widely used in those high-rise structures [1]. The steel frame structure system has low lateral stiffness and large lateral displacement under horizontal load. To solve this problem, the steel frame-shear wall system with corrugated steel plates as natural lateral resistance members was firstly developed in the Occident and Japan. The corrugated steel sheets were first used in Japan, the 1970s as crane beam webs [2]. In 2004, corrugated steel plates and concrete plates were combined and put into share test by Hossain and Wright [3], the results showed that the combined shear walls carried most of the shear force. Fereshteh Emami et al [4] carried out low-cycle repeated loading tests on flat steel shear walls, horizontally placed corrugated plates, and vertically placed corrugated shear walls. The results showed that the energy consumption capacity of corrugated steel shear wall was about 50% higher than that of flat steel shear wall. In the 1970s, mild steel was used as bending beams, torsion beams and U-shaped steel plate energy dampers by Kelly et al [5] in a New Zealand government office building. Subsequently, Sang-Hoon [6] proposed a steel plate damper with openings, which consumed seismic energy by the shear deformation of steel between the holes. Low cycle repeated load tests were...
conducted on this damper and the results showed that it has satisfactory hysteresis performance. G. Gortes et al [7] put the mild steel dampers between the interlayer beams to extend the service of the beams and connections, and performed FEM analysis to summarize the optimal energy consumption. Pan [8] proposed E-shaped steel damper with high-strength mild steel and analyzed its hysteretic behavior and restoring force model. The results showed that this E-shaped steel damper had higher initial stiffness and better hysteresis performance.

Great progress has been made on the bearing capacity of shear wall and damper, the buckling and hysteretic behavior of corrugated plate by the scholars around the world. However, there were little researches on the combination of mild steel damper and corrugated steel plate wall in one steel frame. Based on the researches above, a new lateral resistant system was proposed in this paper: Damping Energy Dissipation Corrugated Steel Plate Shear Wall (DCSW). In this system, the corrugated steel plate served as shear wall for its high stiffness and strong buckling resistance, and mild steel dampers were added as seismic energy consumers.

2. Design of DCSW
The DCSW consists of a steel frame, an infilled corrugated steel plate, and a mild steel damper (Fig. 1a). The size of the one trapezoidal wave of corrugated steel plate is hr=100mm, b=40mm, d=80mm, q=240mm. The corrugated steel plate has a high of 3200 mm, a length of 3000 mm, and a plate thickness of 6 mm (Fig. 1b). The mild steel damper is made of T-shaped mild steel with a diamond-shaped hole in the web (Fig. 1c) with 20 mm width and 124 mm height of a limb.

![Figure 1. DCSW](image)

3. FEM Analysis

3.1. Establishment of finite element model.
The ABAQUS6.14 software was used to simulate the DCSW in this paper. And its lateral bearing capacity and hysteretic behavior were studied. The Bilinear Kinematic Hardening Plasticity (BKIN) model was used as material constitutive model, and the elastic modulus in the of strengthening section of material was 0.01E. The yield criterion of material was Von Mises yield criterion. The steel frame, corrugated steel plate and mild steel damper of the DCSW were Q345 and Q235 grade steel respectively (Table. 1).

| Steel   | E / (N/mm²) | fy / (N/mm²) | Poisson's ratio |
|---------|-------------|--------------|----------------|
| Q235    | 206000      | 235          | 0.3            |
| Q345    | 206000      | 345          | 0.3            |

In this paper, the steel frame, corrugated steel plate and mild steel damper was analyzed by the S4R SHELL unit. Since the materials in the DCSW structure was made all by steel and with regular shape, the mesh was all divided freely with a length of 50 mm.
The connections of the steel frame were rigid connections; thus, the middle beams and the columns were connected by the Merge command in the simulation. Assuming that there was no slip between corrugated plate, damper and steel frame, and those elements were bound to the frame by the Tie command. The boundary conditions of DCSW were listed as follow: the degrees of freedom on the bottom were limited to fix all elements completely; and the degrees of freedom on the web of beams and columns were also limited to avoid the frame overturning.

3.2. Hysteresis Performance Analysis

3.2.1. Hysteresis Performance of Mild Steel Dampers. The low-cycle repeated loading simulation was carried on the mild steel damper of DCSW to analyze the energy consumption capacity. The cyclic load with displacement control was applied to the structure (Fig. 2). The hysteresis curve of the mild steel damper was full and spindle-shaped, which means that the energy consumption capacity of it was excellent. The load-displacement curve of the damper was a straight line in the initial loading phase, showing a high initial stiffness. Then as the loading continues, the deformation of the damper's limb steel increased and entered the plasticity stage. The slope of the curve and the stiffness of the damper decreased. During the unloading stage, the hysteresis curve decreased linearly. The plastic deformation of the damper increased continuously as displacement grew, as well as the hysteresis loop and energy consumption. The maximum forward and reverse bearing capacity of the mild steel damper was 2029kN and 2003kN respectively, which showed high bearing capacity and stability in both directions. The yield displacement was about 3.5mm, which is much smaller than the main structure (steel frame shear system). It was shown that the mild damper could consume energy before the main structure yielded and protect other elements.

![Figure 2. Mild Steel Damper Hysteresis Curve](image)

To analyze the influence of the infill steel plate on the hysteretic behavior of the steel frame-shear wall system, steel frame-flat steel plate shear wall (SS), steel frame-horizontal corrugated plate shear wall (HCSW) and steel frame-vertical corrugated plate shear wall (VCSW) were compared. Those three models were the same except for the infill steel plate.

3.2.2. Hysteresis Performance of Infill Steel Plates. The hysteresis curves and skeleton curves of SS, HCSE, and VCSW were shown in Fig. 3. The SS (Fig. 3a) had a large initial stiffness, and the load increased linearly as displacement of the loading point increased. However, there was a pinching phenomenon as the displacement of the loading point grew. This was because the out-of-plane stiffness of the flat steel plate was low, and the tensile force band was formed under the lateral load. During the reverse load, the tension zone became the compression zone, the out-of-plane deformation occurred and accumulated as the loading carried on.

The hysteresis curves of the HCSW and VCSW (Fig. 3b and 3c) were full and spindle-shaped without pinching phenomenon, which showed that both structures have better bearing capacity than SS. The skeleton curve (Fig. 3d) showed that the forward and reverse load ultimate bearing capacity of HCSW were 3768kN and 3771kN respectively, which were 37% and 41% higher than SS respectively. And that of VCSW were 3805kN and 3838kN respectively, which were 39% and 43% higher than SS.
respectively. Therefore the corrugated steel wall had higher bearing capacity and energy consumption capacity than flat steel wall, and maintains high stability in the positive and negative directions. The direction in which the steel plate is placed has little effect on the hysteresis performance of the structure.

3.2.3. Hysteresis performance analysis of DCSW structure. In order to explore the influence of mild steel damper on the hysteretic behavior of the structure, the finite element simulation results of HCSE and steel frame-damping horizontal corrugated shear wall (D-HCSW), VCSW and steel frame-damping vertical corrugated plate shear wall(D-VCSW) were compared. As shown in Fig. 4a, the hysteresis curves of HCSW and D-HCSW were full shuttle shape, showing a ideal hysteresis performance. At the beginning of the loading, the hysteresis curves of those two specimens were close, while in the end of loading, the deformation of D-HCSW was larger. The ultimate bearing capacity of D-HCSW was 4199kN, but that of HCSW was 3771kN, representing that the adoption of mild steel dampers increased the ultimate bearing capacity by about 11.4%. Fig.4b showed the skeleton curve of those two models, in which red one represented D-HCSW, and blue one represented HCSW. The ultimate bearing capacity of D-HCSW occurred when the loading displacement was 37.5mm, then the bearing capacity begins to degenerate, while that of HCSW was 33mm. It can be seen that the bearing capacity and yield displacement of D-HCSW were improved with mild steel dampers, as well as the hysteresis loop.

Fig. 4c and 4d showed the hysteresis curve and skeleton curve of the VCSW and D-VCSW. The trend of those two specimens were the same as that of HCSW and D-HCSW, but the ultimate bearing capacity of D-VCSW (4300kN) was 13% higher than that of VCSW (3805kN). It can be seen from the shape of the hysteresis curve and the degree of degradation of the skeleton curve that the ductility capacity and energy dissipation of specimens were improved with mild steel dampers.
4. Summary
In order to study the seismic performance and hysteretic behavior of DCSW, three FEM of steel frame-shear wall with different structural were designed put into cyclic loading test. The conclusions were listed as follow:

(a) Hysteresis Curves of HCSW and D-HCSW
(b) Skeleton Curves of HCSW and D-HCSW
(c) Hysteresis Curves of VCSW and D-VCSW
(d) Skeleton Curves of VCSW and D-VCSW

Figure 4. Hysteresis Curves and Skeleton Curves of HCSW, D-HCSW, VCSW and D-VCSW

(1) The lateral resistance performance of corrugated steel sheets was significantly better than that of flat steel sheets. The ultimate bearing capacity and ductility coefficient of the corrugated steel frame-shear wall system were about 23% and 42% higher than that of the flat steel frame-shear wall system respectively.

(2) The hysteresis curve of the mild steel damper was full, the forward and reverse ultimate bearing capacity were 2039kN and 2003kN respectively, showing a high consistency. The yield displacement was about 3.5 mm, which could consume energy before the main structure yielded and protect other elements.

(3) The adoption of mild steel dampers can improve the ductility and lateral resistance of the structure. The bearing capacity of D-HCSW and D-VCSW increased by 11.4% and 13% respectively.

Acknowledgments
The work was sponsored by Natural Science Foundation of Shandong Province (ZR201808010019), Key Research and Development Program of Shandong Province (2015GSF122003; 2016GSF122012), and Project of Shandong Province Higher Educational Science and Technology Program (J17KB048; J18KA208). The writers gratefully acknowledge all the support provided.
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