Design Method of The New Damping Energy Dissipation Corrugated Steel Plate Shear Wall System

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Abstract. In order to improve the lateral stiffness of the steel frame, natural anti-buckling corrugated steel plate shear wall was combined with mild steel dampers, forming a new damping energy-dissipation corrugated steel plate shear wall system (DCSW). The design method of the DCSW system was proposed based on plastic analysis. To study the seismic performance of this system, the nonlinear FEM of the DCSW system was established by ABAQUS, and the analysis on bearing capacity and energy dissipation capacity was carried out. The results showed that the DCSW designed by this method had high lateral bearing capacity and energy dissipation capacity. The lateral ultimate bearing capacity increased by 50% and lateral displacement reduced by 43% with corrugated steel plate shear wall and mild steel dampers.

1. Introduction
Steel plate shear wall structures were widely used in high-rise buildings for their high strength and good ductility. However, the rigidity of the flat steel plate was small, which tended to cause out-of-plate buckling and reduced the bearing capacity of the structure. In this paper, design experience from many research was summarized to proposed a new type of damping corrugated steel plate shear wall with the strategy of “soft but rigidity”. The cross-section of steel shear wall was changed into corrugated steel shear wall instead of the flat steel shear wall. The corrugated steel plate was light in weight and easy to construct, it also would not cause damage to the wall, which made it a natural buckling shear wall. Mild steel dampers were also added to this system to dissipate the seismic energy. Therefore, a new type of damping corrugated steel plate shear wall (DCSW) was formed (Fig. 1).

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 with 20 mm width and 124 mm height of a limb.
According to the previous studies [1-3], corrugated steel webs could increase the buckling critical capacity of the steel plate and decrease its buckling. In this paper, the plate types were chosen as follow (Fig. 2): a=70mm, b=d=50mm, θ=45°, c=70.71mm.

Hollow diamond shaped t-section steel damper (HDSD) was used as the energy dissipating component, which mainly dissipated seismic energy by the T-shaped mild steel web between the diamond-shaped holes [4].

3. FE Design Method of DCSW

3.1 Design of Steel Frame

The beams and columns of steel frame were Q345 steel according to the Code for Load Design of Building Structures (GB50009-2012) [5]. After initially selecting the section of frame beam and column, the internal force of frame beam and column was calculated and checked by PKPM, and the size of section beam and column was adjusted. Finally, the cross-sectional dimensions of frame beams and columns were shown in Table 1.

| Layer | Beam Section Size | Column Section Size |
|-------|-------------------|---------------------|
| 1,2   | HM390×300         | HW394×398           |
| 3,4   | HM340×250         | HW350×350           |
| 5,6   | HM294×200         | HW300×300           |

3.2 Design of Corrugated Steel Plate

After choosing the section size of beam and column, the horizontal seismic force of DCSW system was calculated. According to the Load Code, the load standard value of lightweight concrete block was 2.2 kN/m2, and the snow load of roof was 0.40 kN/m2. The natural vibration period of the structure is formula (1):

\[
T_i = 0.25 + 0.53 \times 10^{-3} \frac{H^2}{\sqrt{B}} = 0.325s
\]

According to the Code for Seismic Design of Buildings[6], the characteristic period of the building was \( T_s = 0.35s \approx T_i > 0.1s \), the damping ratio was 0.05, and the seismic influence coefficient was \( \alpha_i = \alpha_s = 0.16 \). Calculate the horizontal seismic force using the bottom shear method, as in formula (2).
\[ F_i = \frac{G_i H_i}{\sum_j G_j H_j} \quad (2) \]

\[ F_{EK} = \alpha_i G_{eq} G_{ey} = 0.85 \sum G_i H_i \quad \text{Height of each floor (3.6m),} \]

The steel used for corrugated steel plate was Q235. Assuming that the horizontal force was borne by DCSW system, the shear capacity \( \tau_{lH} \) provided by corrugated steel plate should be greater than the horizontal seismic force \( \gamma_R V_i \) \[7\]. The minimum thickness of the steel plate was satisfied:

\[ \tau_{lH} > \gamma_R V_i \gamma_R V_i \quad (3) \]

According to the Technical Regulations for Steel Structures for High-Rise Civil Buildings (JGJ988-98) \[8\], in order to effectively exert the performance of the steel plate after buckling, the steel plate wall should adopt shear buckling as the ultimate design state, and the maximum thickness of the steel plate satisfies:

\[ t_s < \frac{H_i}{100} \left\{ \frac{\tau}{\sqrt{123+93\left(\frac{l}{H}\right)^2}} \right\} \quad (4) \]

Calculated the upper and lower limits of the thickness of the corrugated steel plate according to formulas (3) and (4), the thickness of the corrugated steel wall was shown in Table 2:

| Number of layers | layer | Second floor thickness | Three floors thickness |
|------------------|-------|------------------------|-----------------------|
| thickness        | 7mm   | 6mm                    | 6mm                   |
| Number of layers | Four floors | Five floors | Six floors |
| thickness        | 6mm   | 5mm                    | 5mm                   |

3.3 Design of Mild Steel Damper
In this paper, the diamond-shaped opened T-shaped mild steel damper was selected to open the hole in the web and transformed the limb steel between the holes to achieve multi-point yield energy \[9,10\].

![DCSW System Force Analysis](image)

The T-shaped steel model had a wide flange of 200×200×8×13(Fig 3), which was calculated by one-piece steel plate, and simplified as a fixed-beam at both ends. The calculation was shown in Fig 4.

![Calculation of Diamond-shaped Open-hole T-shaped Mild Steel Damper](image)

(a) Damper single limb  (b) calculation sketch  (c) Moment diagram

According to formula (5), the moment of inertia of the cross section to the neutral axis could be obtained.

\[ I_z = \frac{tb^3}{12} \quad (5) \]

The single-leg steel plate of the damper was simplified to a fixed beam at both ends. The elastic stiffness can be obtained from formula (6):
\[ k_d = cn \frac{12EI}{(h)^3} = cn \frac{Et^3}{(h)^3} \]  

When the lateral load increased, the cross-section bending moment increased, and the damper web began to enter the plastic stage. The angle of rotation of the single-leg steel plate was \( \theta_p \). When the cross-section of the single-leg steel fully enters the plastic stage, the bending moment \( M \) can be obtained by formula (7):  

\[ M_p = \sigma_y \frac{tb^2}{4} \]  

From the conservation of energy:  

\[ p_y \delta_p = 2nM_p \theta_p \]  

In the formula, \( p_y \) was yield load of mild steel damper, \( \delta_p \) was plastic displacement of mild steel dampers, \( \theta_p \) was plastic corner of soft steel damper. The simplified diagram can be obtained from Figure 5:  

\[ \delta_p = h \tan \theta_p \]  

When \( \theta_p \) was small, \( \tan \theta_p = \theta_p \), then \( \delta_p = h \theta_p \). The formulas (7) and (8) and the results were as follows:  

\[ P_y = \frac{2nM_p}{h} = \frac{n\sigma_y tb^2}{2h} \]  

\[ \delta_p = 0.5e_y (h)^2 / b \]  

The initial stiffness, yield strength and yield displacement of the diamond-shaped open T-shaped mild steel damper were calculated according to equations (9) and (10) (11) to design the limb width, limb height and limb number of the damper. The damper dimensions were shown in Table 3.  

| Number of layers | Layer  | Second floor | Three floors |
|------------------|--------|--------------|--------------|
| Limb width       | 33mm   | 32mm         | 30mm         |
| Number of layers | Four   | Five         | Six          |
| Limb width       | 28mm   | 24mm         | 19mm         |

### 4. Finite element simulation

![Figure 5. DCSW System Force Analysis](image)

The nonlinear finite element model is established by using ABAQUS finite element analysis software, as shown in Fig. 5. The steel frame and the embedded corrugated steel plate and the mild steel damper are all modeled by shell element, using SR4 unit; the steel constitutive relation is bilinear. Following the reinforced constitutive model, the steel frame beam-column joints adopt rigid nodes, and the beams and columns are combined to form a whole by the merge option in the assembly function module to realize the establishment of rigid nodes; the loading system is displacement control.
Figure 6 shows the load-displacement curve of the structure, the black curve represents the DCSW system, and the red curve represents the steel frame structure. Comparing the deformation of the structure in the range of 15 cm, when subjected to the same horizontal load, the apex side shift of the DCSW system is less than the 43% apex lateral displacement of the steel frame and yields earlier than the steel frame.

When the displacement value of the steel frame structure is 15 cm, the ultimate bearing capacity of the structure is 3509.2 kN; when the displacement of the DCSW system is 13.2 cm, the ultimate bearing capacity of the structure is 5009.4 kN, and the ultimate bearing capacity of the DCSW system is increased by about 50% compared to the steel frame.

5. Summary
(1) DCSW can make full use of the performance of mild steel dampers and corrugated steel plates to avoid premature buckling of steel plate shear walls, improve the lateral resistance of the structure, and reduce the 43% apex displacement of the steel frame.

(2) The DCSW system under the design method has good seismic performance, high ductility and 50% higher bearing capacity than ordinary steel frame shear wall structure.

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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