Design and numerical simulation of a new type of staged yield mild steel damper

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Abstract. In order to make up for the lack of single form of energy dissipation of the existing mild steel dampers, a new type of staged yield mild steel damper is proposed by combining two different forms of energy dissipation steel plates. Its construction and energy dissipation mechanism are introduction, based on the relevant theory, the expression of mechanical properties parameters are derived, and the finite element software ABAQUS is used to simulate the staged yield mild steel damper with different parameters. The results show that the staged yield mild steel damper not only possesses full hysteretic loops and excellent energy dissipation capacity, but also achieves staged yield function effectively. The height of the staged yield mild steel damper is an important factor affecting its yield displacement and hysteretic performance.

1. INTRODUCTION

Traditional seismic structures mainly rely on improving the load-bearing and deformation capacity of the structure to resist earthquakes, although the collapse of the structures can be avoided, it is difficult to repair the main structural components after damage, which brings people incalculable property losses. As a typical structural passive control technology, energy dissipation technology refers to the installation of dampers in the key parts of the structure. Under the earthquake action, the relative deformation or velocity of dampers is used to provide additional damping and stiffness for the main structure, so as to reduce the seismic response and damage of the main structure and achieve the purpose of energy dissipation.

Since the American scholar YAO J.T.P.¹ proposed the concept of structural vibration control in 1972, scholars from all over the world have carried out in-depth research in the field of energy dissipation. Among many metal dampers, mild steel dampers not only have stable hysteretic performance and good fatigue performance, but also have simple structure and convenient installation and replacement. They have been widely used in practical engineering. At present, the mild steel dampers developed at home and abroad mainly include U-shaped steel dampers², stiffening dampers³-⁴ and circular dampers⁵, etc. This kind of damper mainly uses the out-of-plane plastic hysteretic deformation of steel plate to dissipate seismic energy, and belongs to the bending yield mild steel damper. In addition, some scholars have proposed shear yield mild steel damper⁶-⁷, which is based on the in-plane deformation of the steel plate. Such damper has the characteristics of large initial stiffness, small yield displacement, high bearing capacity and strong energy dissipation capacity after yielding. According to the different stress forms of
mild steel dampers, it can also be divided into axial yield and torsion yield mild steel dampers. However, most of the mild steel dampers have a single form of energy dissipation, and energy dissipation occurs only under moderate or large earthquakes. Under small earthquakes, they provide certain lateral stiffness but do not have energy dissipation capacity, which is not conducive to the effective protection of the main structure.

Aiming at the lack of single energy dissipation form of existing mild steel dampers, a new type of staged yield mild steel damper is proposed in this paper. The staged yield mild steel damper is composed of two different forms of energy dissipation steel plates, by adjusting the size parameters of the energy dissipating steel plate, the damper has different yield displacements, thereby achieving the goal of staged yield energy dissipation. Through the finite element analysis software ABAQUS, the staged yield mild steel damper proposed in this paper is simulated to verify the feasibility of staged yield and energy dissipation performance.

2. STAGED YIELD MILD STEEL DAMPER

2.1. Structure form

The schematic diagram of the staged yield mild steel damper is shown in Fig.1, it is composed of X-shaped damper and annular damper. The structure of the staged yield mild steel damper is shown in Fig.2, the top and bottom of the X-shaped damper are respectively connected with the inner surface of the annular damper by welding, so as to ensure the deformation of both under horizontal load. The upper surface and the lower surface of the annular damper are respectively provided with a number of bolt holes for the installation of the damper in the energy dissipation part of the structure.

![Fig.1 Schematic diagram of the staged yield mild steel damper](image)

![Fig.2 Structure of the staged yield mild steel damper](image)

2.2. Energy dissipation mechanism

The staged yield mild steel damper proposed in this paper combines the X-shaped damper and the annular damper through reasonable stiffness matching to make them work together. At the same time, the difference in the yield strength of different steels is used to further increase the yield displacement of the X-shaped damper and the annular damper, thereby realizing the characteristic of staged yield. Under the action of small earthquake, the X-shaped damper first achieves its yield strength and begins to dissipate energy under small displacement, while the annular damper maintains its elastic state and can provide certain lateral stiffness for the structure, which is the first stage of energy dissipation. Under moderate or large earthquake, the annular damper achieves its yield strength at large displacement, and
dissipates the seismic energy together with the X-shaped damper, which is the second stage of energy dissipation.

3. MECHANICAL PROPERTIES

3.1. Mechanical properties of X-shaped damper

The X-shape damper dissipates energy through the lateral bending deformation of the energy dissipation steel plate. Its biggest advantage is that under the load, all points along the height direction of the energy dissipation steel plate can yield at the same time, which makes the plastic performance of the steel plate material fully play, and is conducive to improving the energy dissipation capacity of the damper. The neck width of the X-shaped damper is small, which can only transfer the shear force, so it can be simplified as the shape shown in Fig.3. The height of the energy dissipation steel plate is \( h \), the width is \( b \), and the thickness is \( t_1 \).

Fig.3 Calculation diagram of X-shaped damper

Under the action of horizontal load, when the outermost fiber of the fixed end of the energy dissipation steel plate just reaches the yield, the horizontal load is defined as the yield load of the X-shaped damper, and the displacement of the fixed end of the energy dissipation steel plate is defined as the yield displacement of the X-shaped damper. According to reference\(^8\), it is deduced that the initial stiffness \( K_a \), yield load \( F_a \) and yield displacement \( \Delta_a \) of the X-shaped damper can be calculated by the following formula respectively.

\[
K_a = \frac{2E_b t_1^3}{3h^3}
\]

\[
F_a = \frac{M_y}{h} = \frac{1}{6} \frac{bt_1}{h^2} f_{y1} = \frac{f_{y1}bt_1^2}{3h}
\]

\[
\Delta_a = \frac{F_a}{K_a} = \frac{f_{y1}h^2}{2E_b t_1}
\]

Where, \( M_y \) and \( I(y) \) are respectively the moment and the section moment of inertia at the height \( y \) of the energy dissipating steel plate. \( E_b \) is the initial elastic modulus of steel. \( M_y \) is the yield moment for the fixed end of the energy dissipation steel plate. \( f_{y1} \) is the yield strength of steel.

3.2. Mechanical properties of annular damper

The annular damper is connected with the main structure in the horizontal section by bolts, which is equivalent to a fixed connection. Therefore, the annular damper can be regarded as a series connection of two U-shaped dampers on both sides, each U-shaped damper includes an arc section and upper and lower straight sections (see Fig.4). The main geometric parameters of the annular damper are the thickness of the steel plate \( t_2 \), the width of the steel plate \( B \), the bending radius \( R \) and the length of the straight section \( L \), among which is the distance from the end of the arc section to the nearest X-shaped...
energy dissipation steel plate. According to reference[9], the theoretical calculation formulas of the initial
stiffness $K_b$, yield load $F_b$ and yield displacement $\Delta_b$ of the annular damper are derived as follows.

\begin{align*}
K_b &= \frac{E_b t_1^3}{3R^2(\pi R + 4L)} \quad (4) \\
F_b &= \frac{2f_y t_1^2}{(t_1 + 4R)} \quad (5) \\
\Delta_b &= \frac{6f_y R^2(\pi R + 4L)}{E_f t_1(t_1 + 4R)} \quad (6)
\end{align*}

Where, $E_b$ and $f_y$ are respectively the initial elastic modulus and yield strength of steel.

### 3.3. Mechanical properties of staged yield mild steel damper

The energy dissipation steel plate of X-shaped damper designed in this paper adopts LYP160 steel with
low yield point, which can yield and dissipate energy under small displacement under small earthquake,
but its load-bearing capacity is limited. Q235 steel is used as energy dissipation steel plate of annular
damper, which has large load-bearing capacity, but it can only yield and dissipate energy under medium
and large earthquakes. The staged yield mild steel damper is composed of X-shaped damper and annular
damper. It can not only dissipate energy with small displacement, but also provide large load-bearing
capacity, and has the characteristics of staged yield. Its mechanical properties can be regarded as the
superposition of X-shaped damper and annular damper. The load-displacement curve of the staged yield
mild steel damper is shown in Fig.5. The initial stiffness $K_1$, the first yield load $P_{y1}$, the first yield
displacement $\Delta_{y1}$ and the second yield displacement $\Delta_{y2}$ can be calculated according to equations (7) to
(10).

\begin{align*}
K_1 &= mK_0 + K_b \quad (7) \\
\Delta_{y1} &= \frac{f_y h_2}{2E_f t_1} \quad (8)
\end{align*}
\[ \Delta z = \Delta_k = \frac{6f \cdot R^2 (\pi R + 4L)}{E \cdot \Delta (t_2 + 4R)} \]  
\[ P_{ij} = K_i \Delta = (mK_i + K_s) \cdot \Delta_a \]  \hspace{1cm} (9) \hspace{1cm} (10)

Where, \( m \) is the number of X-shaped damper.

### 3.4. Design parameters of staged yield mild steel damper

Through the analysis of the mechanical performance parameters of the staged yield mild steel damper, it can be seen that the yield displacement is mainly affected by the height of the mild steel damper, the thickness of the energy dissipation steel plate and the yield strength of the steel. In order to study the influence of the height of staged yield mild steel damper on its yield displacement and hysteretic performance, three X-shape damper models SP-1~SP-3, three annular damper models SP-4~SP-6 and three whole models WP-1~WP-3 (namely, staged yield mild steel damper model) are designed in this section. The geometric parameters of X-shaped damper and annular damper are shown in Fig.6, and the specific size parameters of each specimen are shown in Table 1.

![Fig.6 Geometric parameters of whole model](image)

| Model number | X-shaped damper | annular damper |
|--------------|-----------------|----------------|
|              | \( t_1 \) | \( h \) | \( b_1 \) | \( b_2 \) | \( t_2 \) | \( D \) | \( B \) | \( L \) |
| SP-1         | 14             | 250           | 180         | 30          | 30          | 280 | 180 | 120 |
| SP-2         | 14             | 275           | 180         | 30          | 30          | 305 | 180 | 120 |
| SP-3         | 14             | 300           | 180         | 30          | 30          | 330 | 180 | 120 |

The size parameters of each specimen in Table 1 are substituted into the theoretical formulas (1) and (4) for calculation. It can be seen that the initial stiffness of the annular damper is about 4-5 times of that of the X-shaped damper. Therefore, the whole model specimen can be composed of one annular damper model and five X-shaped damper models respectively.

### 4. FINITE ELEMENT ANALYSIS

#### 4.1. Establishment of finite element model

The finite element analysis software ABAQUS is used for modeling analysis. Both the X-shaped damper and the annular damper adopt deformable solid elements, and the element type adopts an 8-node hexahedral linear reduction integral element (C3D8R). For the whole model specimen, the top and bottom of the X-shaped damper are connected with the upper and lower inner surfaces of the annular damper by tie to simulate the welding effect between steel plates. The reference points RF1 and RF2 are respectively established on the upper and lower outer surfaces of the annular damper. The lower surface is coupled with the reference point RF2, and the six degrees of freedom of the reference point RF2 are constrained at the same time, which is equivalent to the fixed connection. The upper surface is coupled with the reference point RF1, releasing only the translational degrees of freedom in X direction. In order to simulate more accurately, four layers of grids are divided along the thickness direction of the energy
dissipation steel plate. Von Mises is used as the yield criterion, and bilinear follow-up strengthening model is used as the constitutive model. Among them, the elastic modulus of steel $E = 2.06 \times 10^5$ MPa, Poisson's ratio $\nu = 0.3$.

For X-shaped damper models SP-1~SP-3, annular damper models SP-4~SP-6 and whole models WP-1~WP-3, in order to obtain the corresponding yield displacement and yield load, a monotonic loading method is adopted, and the target displacement is 30mm. For the whole model specimens WP-1~WP-3, in order to obtain its energy dissipation characteristics and related parameter values, the cyclic displacement loading method is adopted, maximum loading displacement amplitude is 30mm. The loading diagram is shown in Fig.7.

![Fig.7 Loading system](image)

### 4.2. Model validation

In order to verify the correctness of the modeling method in this paper, the specimen LS-2 of annular steel plate damper in reference [10] is selected for modeling, and the same loading system as the test is adopted. Fig.8 shows the comparison of the hysteretic curves between the test and the finite element simulation. It can be seen that the overall shape of the hysteretic curves between the test and the finite element simulation is very close, especially the initial stiffness and unloading stiffness are in good agreement. Therefore, the modeling method can simulate the mild steel damper better, and can be used for the subsequent analysis and research of the staged yield mild steel damper proposed in this paper.

![Fig.8 Comparison of the hysteretic curve](image)

### 4.3. Comparison between theoretical calculation and numerical simulation

The load-displacement curve as shown in Fig.9 is obtained by monotonic loading simulation of X-shaped damper model, annular damper model and whole model (the load of SP-1 ~ SP-3 is the sum of five X-shaped damper models). The finite element analysis values (FE) and theoretical calculation
values (TC) of the initial stiffness and the first yield load of the whole model are listed in Table 2, the first yield displacement and the second yield displacement are listed in Table 3. The theoretical calculation values are calculated according to the formula given in Section III. It can be seen from Table 2 and Table 3 that the finite element analysis values of the first yield load and the second yield displacement of the whole model WP-1~WP-3 are in good agreement with the theoretical calculation values, while there are some errors between initial stiffness and the first yield displacement, but they are all controlled within 15%. Therefore, if the theoretical formula is used to calculate the mechanical performance parameters of staged yield mild steel damper, it is suggested to multiply the initial stiffness calculation result by the check factor of 0.85 and the first yield displacement calculation result by the check factor of 1.15.

![Monotonic loading curve](image)

Fig.9 Monotonic loading curve

The yield displacement of the X-shaped damper model SP-1~SP-3 correspond to the first yield displacement of the whole model WP-1~WP-3, the yield displacement of the annular damper model SP-4~SP-6 correspond to the second yield displacement of the whole model WP-1~WP-3. It can be seen that the yield displacement of the X-shaped damper is significantly smaller than that of the annular damper, so the staged yield mild steel damper can effectively achieve the characteristics of staged yield.

| Table 2  | Initial stiffness and first yield load |
|----------|---------------------------------------|
| Whole model | Initial stiffness/mm | Ratio | First yield load/kN | Ratio |
|           | FE     | TC      |         | FE     | TC      |         |
| WP-1      | 34.22  | 40.22   | 0.85    | 67.42  | 69.58   | 0.97    |
| WP-2      | 26.82  | 31.27   | 0.86    | 64.37  | 65.67   | 0.98    |
| WP-3      | 21.63  | 24.83   | 0.87    | 61.65  | 62.08   | 0.99    |

| Table 3  | Yield displacement |
|----------|---------------------|
| Model number | Yield displacement/mm | Ratio |
|            | FE   | TC   |         | First yield displacement | Second yield displacement |
| SP-1       | 1.97 | 1.73 | 1.14    | 1.14                        |
| SP-2       | 2.40 | 2.10 | 1.14    |                            |
| SP-3       | 2.85 | 2.50 | 1.14    |                            |
| SP-4       | 6.30 | 6.67 | 0.94    |                            |
| SP-5       | 7.05 | 7.61 | 0.93    |                            |
| SP-6       | 8.10 | 8.60 | 0.94    |                            |
4.4. Hysteresis curve
Fig. 10 shows the hysteresis curves of the whole model WP-1 \( \sim \) WP-3. The hysteresis curves of the whole model WP-1 \( \sim \) WP-3 are similar in appearance and relatively full and stable, without obvious pinching phenomenon, and are generally spindle-shaped, indicating that the staged yield mild steel damper has superior energy dissipation performance and deformation capacity. At the initial stage of loading, because the initial stiffness of the specimen is larger and the plastic deformation is smaller, the energy dissipation is less. With the increase of loading displacement, the stiffness of the specimen decreases gradually, and the area surrounded by the hysteretic curve increases gradually, which indicates that the energy dissipation capacity of the specimen is increasing. It can be seen from Fig. 10 that the hysteretic curve of WP-1 is the fullest, followed by WP-2, and WP-3 is the smallest.

![Hysteresis curves of the whole model](image)

Fig. 10 Hysteresis curves of the whole model

4.5. Skeleton curve
Fig. 11 shows the skeleton curves of WP-1 \( \sim \) WP-3. According to Fig. 11, the skeleton curve of the whole model WP-1 \( \sim \) WP-3 is symmetrical and has the same development trend, and it is inverted Z-type as a whole. At the initial stage of loading, the skeleton curve of the specimen is relatively close. After entering the elastic-plastic stage, the load-bearing capacity of WP-1 is the largest, followed by WP-2, and the load-bearing capacity of WP-3 is the smallest. This is because the increase of the specimen height reduces the overall lateral stiffness of the staged yield mild steel damper. At the same time, it can be seen that the greater the initial stiffness of the specimen, the smaller the yield displacement, and the stronger the plastic deformation ability of the specimen after it enters yield.

![Skeleton curves of WP-1 \( \sim \) WP-3](image)

Fig. 11 Skeleton curves of WP-1 \( \sim \) WP-3

4.6. Energy dissipation performance evaluation
The equivalent viscous damping ratio is a key indicator for evaluating the energy dissipation performance of a structure or component. It is a variable that changes with displacement. The larger the
equivalent viscous damping ratio, the stronger the energy dissipation capacity of the structure or component. Fig.12 shows the curves of equivalent viscous damping ratio of WP-1 ~ WP-3 with displacement. It can be seen from Fig.12 that when the loading displacement reaches 30mm, the maximum equivalent viscous damping ratios are 0.40, 0.39 and 0.37 respectively, which indicates that the staged yield mild steel damper has good energy dissipation capacity, and the energy dissipation capacity of the specimen decreases with the increase of the height of the damper.

![Equivalent viscous damping ratio of whole model](image1)

**Fig.12** Equivalent viscous damping ratio of whole model

### 4.7. Stiffness degradation analysis

Fig.13 shows the stiffness degradation curves of the whole model WP-1 to WP-3. It can be seen from Fig.13 that under the action of cyclic loading, the stiffness of WP-1~WP-3 all have different degrees of degradation, but the stiffness degradation process is basically similar. The stiffness degradation is relatively rapid at the initial stage of loading, and tends to be flat in the later stage of loading, and finally stabilizes near a certain limit value. The smaller the height of the mild steel damper, the greater the limit value.

![Stiffness degradation curves of the whole model](image2)

**Fig.13** Stiffness degradation curves of the whole model

### 5. CONCLUSION

Aiming at the lack of single energy dissipation form of existing mild steel dampers, a new type of staged yield mild steel damper is proposed in this paper. The mechanical properties and energy dissipation properties were studied by combining theoretical derivation and numerical simulation. The conclusions are as follows.

(1) The theoretical calculation formula derived in this paper can accurately predict the first yield load and the second yield displacement of the staged yield mild steel damper. For the initial stiffness and the
first yield displacement, the theoretical calculation values should be multiplied by the check factors of 0.85 and 1.15.

(2) The whole model WP-1～WP-3 have full and stable hysteresis curves and good energy dissipation capacity. As the height of the staged yield mild steel damper decreases, its load-bearing capacity and deformation capacity are significantly improved. Therefore, appropriately reducing the height of the staged yield mild steel damper helps to better exert its hysteretic performance.

(3) The equivalent viscous damping ratio of the whole model WP-1～WP-3 gradually increases with the increase of the loading displacement, and the smaller the height of the staged yield mild steel damper, the greater the equivalent viscous damping ratio, the stronger energy dissipation capacity. The equivalent stiffness gradually decreases with the increase of the loading displacement, and finally tends to a certain limit value, the smaller the height of the staged yield mild steel damper, the greater the limit value.

(4) In this paper, a new type of staged yield mild steel damper is discussed, but there is still a lack of experimental research, so it is necessary to carry out related work in the future research.

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