Experimental Study on Mechanical Properties of Shear-type Mild Steel Damper

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***Abstract*—Because of its good energy dissipation capacity and stable performance, the mild steel damper is widely applied in energy dissipation structure. The theoretical model of shear type metal damper was analyzed and calculation formula of the main mechanical parameters was established. Material test of domestic steel BLY160 and Q235 was conducted. On the basis of theoretical analysis and material performance, two groups of dampers with the same dimension but different energy dissipation materials were designed and made. Pseudo-static test on the two groups of specimens was carried out. The test results show that the hysteretic curves of mild steel dampers were full and mechanical properties were stable. Yield strength, yield displacement and other mechanical parameters showed small dispersion. Under Low cycle fatigue loading with ±20mm displacement, the performance of damper with BLY160 was better than that made by Q235.**[1]

***Index Terms*—mild steel damper, hysteretic energy dissipation, yield force, fatigue**

I. INTRODUCTION

China is located on the junction of the circum-Pacific seismic belt and the Eurasian seismic belt, and the earthquake disaster problem is prominent. In the past decade, many severe earthquakes have occurred in China, such as the 2008 Wenchuan earthquake in Sichuan, the 2010 Yushu earthquake in Qinghai, and the Ya'an earthquake in Sichuan in 2013. Wenchuan earthquake caused 69000 deaths, 18000 people disappeared. A large number of buildings such as hospitals, teaching buildings collapsed in the earthquake [1]. Faced with the serious threat of earthquake disasters, it is imperative to vigorously develop advanced seismic technologies

The concept of structure control was proposed by J.T.P.Yao [2], that is, energy-consuming devices were set in the structure to achieve the goals of active control or passive control. As an effective passive control technology, energy dissipation technology has attracted the attention of many scholars once it was proposed. Its main purpose is to provide energy dissipation components in the structure to add effective damping to the structure to reduce the seismic response of the structure [3]. Among various types of energy absorbers, metal dampers are widely used due to their advantages of low cost and ease of replacement. The concept of a metal damper was originally proposed by Kelly et al [4]. As a non-structural component, a metal damper uses its plastic deformation to consume part of the seismic energy, ensuring the safety of the main structure under seismic action. Chinese scholars have researched and developed different types of metal dampers, according to the energy dissipation mechanism, there are mainly bent, sheared, and extruded metal dampers [5-8]. Among the many types of dampers, shear-type mild steel dampers have the advantages of simple structure, easy processing, clear mechanism, and large energy dissipation.

In this paper, the calculation model of the shear-type mild steel damper was analyzed; the expression of the key parameters of the metal damper was deduced. Two types of shear-type metal dampers with domestic low yield point steel BLY160 and ordinary steel Q235 as energy dissipation shear plates were designed and manufactured. Experiment was conducted on the designed specimens to find their basic mechanical properties and low cycle fatigue properties

II. COMPUTING MODEL OF THE SHEAR-TYPE MILD STEEL DAMPER

The shear-type mild steel damper studied in this paper is composed of energy dissipation plate (EDP), flange plates (FPs), stiffeners, and connecting plates (CPs). The schematic diagram is shown in Fig. 1. According to the force characteristics of the damper, the calculation model is simplified, and the theoretical expressions of several key parameters, such as initial stiffness, yield force and yield displacement, are analyzed.

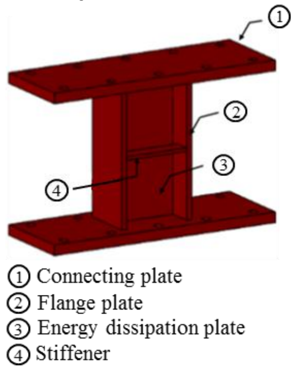

Figure 1. Schematic diagram of shear panel damper

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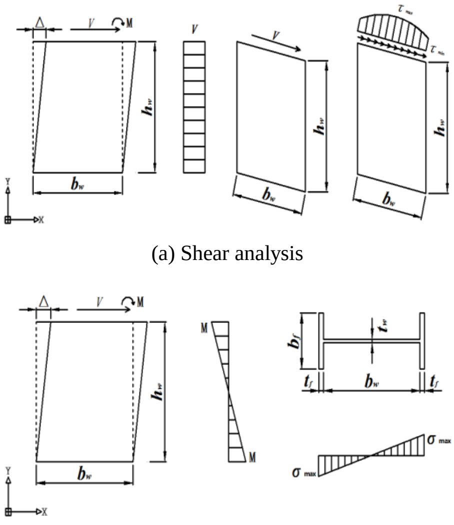


(a) Shear analysis

(b) Bending analysis

Figure 2. Calculating diagram of shear panel damper

A. Initial Stiffness

Fig. 2 shows the computing model, the deformation of mild steel damper is caused by the interaction of shear force and bending moment, it's defined as follow:

$$\Delta=\Delta_V+\Delta_M \tag{1}$$

Where Δ represents the relative horizontal deformation between upper and lower connecting plates, Δ_V and Δ_M represent shear deformation and bending deformation.

Poisson's ratio of steel is usually 0.3. Accordingly, the relationship between the elastic modulus and the shear modulus is as follow:

$$G=\frac{E}{2(1+\nu)}\approx 0.4E \tag{2}$$

According to the principle of basic structural mechanics, shear stiffness K_V and bending stiffness K_M can be obtained:

$$\Delta_V=\int\overline{V}(y)d\eta=\int\overline{V}(y)\frac{V(y)}{GA(y)}dy \tag{3}$$

$$K_V=\frac{V}{\Delta_V}=\frac{GA}{h_w}=\frac{2EA}{5h_w}=\frac{2Eb_wt_w}{5h_w} \tag{4}$$

$$K_V=\frac{V}{\Delta_V}=\frac{GA}{h_w}=\frac{2EA}{5h_w}=\frac{2Eb_wt_w}{5h_w} \tag{5}$$

$$K_M=\frac{12EI}{h_w^3}=E\frac{\left[(b_w+2t_f)^3b_f-b_w^3(b_f-t_w)\right]}{h_w^3} \tag{6}$$

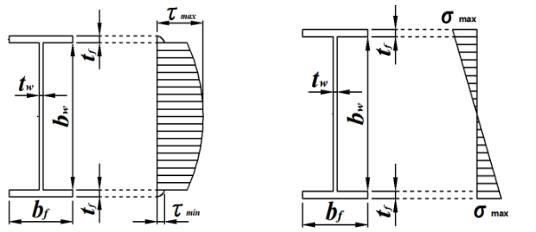
where $\overline{V}(y)$ is the shear force due to the unit load, $V(y)$ is the shear force applied to the damper. Here $\overline{V}(y)=1$ and $V(y)=V$. b_w, t_w and h_w represent the width, thickness, and height of EDP, respectively. A is the sheared area of the EDP. $\overline{M}(y)$ is the bending moment due to the unit load; $M(y)$ is the bending moment applied to the damper; $\overline{M}(y)=y$, $M(y)=V*y$; b_f, t_f represent the width, thickness of the FPs on both sides whose height is the same as the EDP, I is the moment of inertia of the cross-section for FPs on the neutral axis of the EDP along its thickness.

According to equation (4) and (6), the expression of the initial stiffness K_1 for shear-type metal damper has been derived:

$$K_1=\frac{1}{\frac{1}{K_V}+\frac{1}{K_M}}=\frac{1}{\frac{5h_w}{2Eb_wt_w}+\frac{h_w^3}{E\left[(b_w+2t_f)^3b_f-b_w^3(b_f-t_w)\right]}} \tag{7}$$

B. Yield Force and Yield Displacement

The shearing stress on both sides of the shear damper is relatively small compared to the EDP, as shown in Fig. 3 (a), so the shear force of the damper is mainly borne by the EDP. The bending moment of the shear-type mild steel damper is mainly borne by the FPs on both sides. The distribution of the bending normal stress is shown in Fig. 3 (b).



(a) Shearing stress distribution (b) Bending stress distribution

Figure 3. The stress distribution of mild steel shear panel damper

The middle section of the EDP can be approximated as a pure shear state, by Von Mises yield criteria:

$$\frac{1}{\sqrt{2}}\sqrt{(\sigma_x-\sigma_y)^2+(\sigma_y-\sigma_z)^2+(\sigma_z-\sigma_x)^2+6(\tau_{xy}+\tau_{yz}+\tau_{zx})^2}=f_y \tag{8}$$

In which, σ_x, σ_y and σ_z represent principal stress in the three directions of three principal directions, respectively. τ_{xy}, τ_{yz} and τ_{zx} represent three dimensional shearing stress.

The yield condition of EDP is given:

$$\tau_y=\frac{f_y}{\sqrt{3}} \tag{9}$$

The shearing stress distribution of EDP can be considered uniform, yield force (F_y) is obtained:

$$F_y=\alpha A\tau_y=\alpha\frac{b_wt_wf_y}{\sqrt{3}} \tag{10}$$

where α ($\alpha>1$) is conversion coefficient for yield point (CCYP), its value can be determined according to the test results.

Considering shearing and bending deformation, yield displacement (D_y) is given:

$$D_y = \frac{V_y}{K_0} = \alpha \frac{b_w t_w f_y}{\sqrt{3}} \left\{ \frac{5h_w}{2Eb_w t_w} + \frac{h_w^3}{E\left[(b_w + 2t_f)^3 b_f - b_w^3 (b_f - t_w)\right]} \right\} \quad (10)$$

III. Test Overview

A. Material Performance Test

In order to study the energy dissipation mechanism and performance of the shear-type mild steel damper, the basic mechanical properties of the domestic low yield point steel BLY160 and ordinary steel Q235 were obtained by tensile test first, which was an important reference for damper design. Seven standard specimens were made using two kinds of steel, Fig. 4 shows the size marking of standard specimen and the specific geometric parameters were listed in Table I. As showed in Fig. 5, extensometer was used to measure the effective deformation of the specimen. Average test results of two groups of steel specimens are showed in Table II.

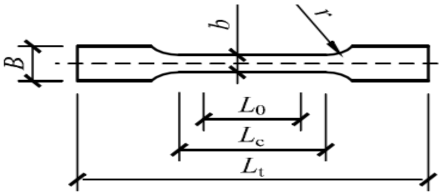
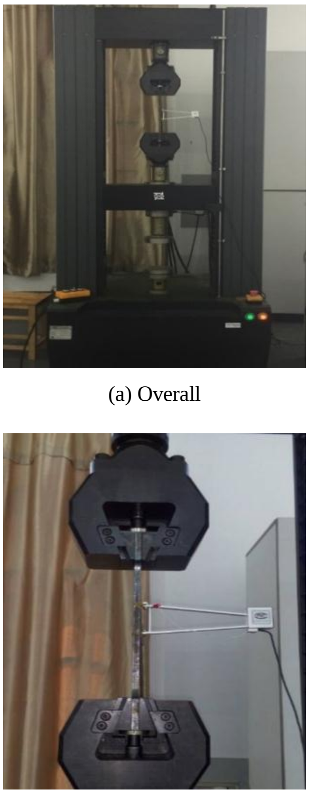


Figure 4. Size marking of material specimens



(a) Overall

(b) Local

Figure 5. The tensile test of steel

TABLE I. Size of Material Specimens

Material	No.	t (mm)	b (mm)	B (mm)	r (mm)	L_c (mm)	L_t (mm)	L_0 (mm)
BLY160	1~7	10	12	24	20	80	200	60
Q235	1~7	6	8	20	20	80	200	50

TABLE II. Tensile Test Results for Steel

Material	Elastic module (GPa)	Yield strength (N/mm2)	Ultimate strength (N/mm2)	Yield ratio (%)
BLY160	200	196	282	70
Q235	200	267	419	64

B. Damper Design

In the experiment, A-type dampers and B-type dampers of the same size were designed and manufactured, and three specimens were made for each type. Among them, the A-type damper EDP adopts low yield point steel BLY160, other parts adopt Q345, named A1, A2, and A3; EDP of B-type damper adopts Q235, and other parts adopt Q345, named B1, B2, and B3. The design dimensions of the various parts of the two types of dampers are shown in Table III.

TABLE III. The Size of Each Component of Dampers

Component	Height/mm	Width/mm	Thickness/mm
EDP	500	260	6
FP	500	160	16
Stiffener	260	30	6
CP	600	250	30

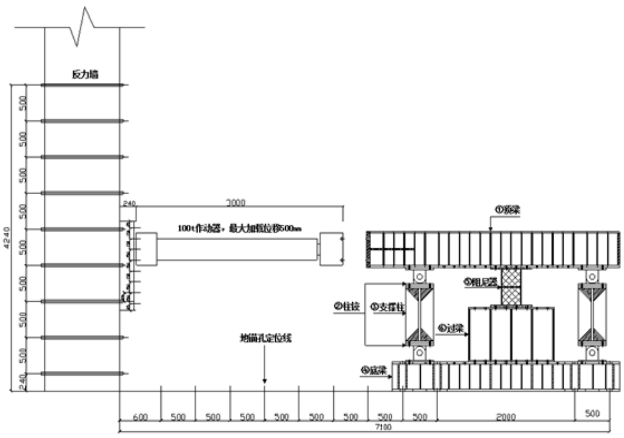


Figure 6. Loading system

The basic mechanical property (BMP) and fatigue resistance (FR) of the dampers were tested in the Civil Engineering and Disaster Prevention and Mitigation Key Laboratories of Jiangsu Province. The power plant uses the 243 type actuator and oil source system produced by MTS. The damper was connected to the parallelogram mechanism through the steel beam and the damper test loading system is formed with the power device, as shown in Fig. 6. The test adopts displacement control, the loading frequency is 0.02Hz, and the displacement time history used in the BMP tests is a triangular amplitude wave. The loading rule is shown in Fig. 7. Some of the specimens were tested with fixed amplitude (15mm or 20mm) cyclic loading to study the fatigue performance after BMP test. The specific arrangement is shown in Table IV.

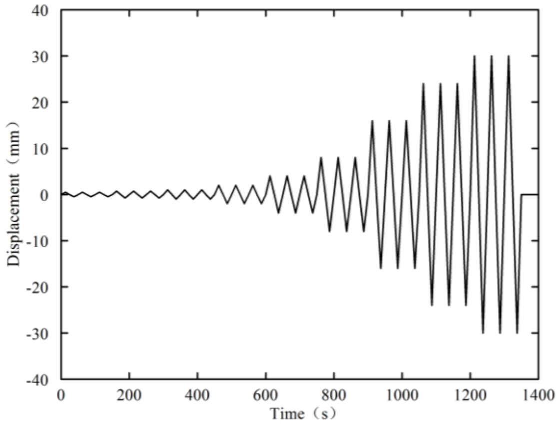


Figure 7. Cyclic displacement history

TABLE IV. LOADING SCHEME

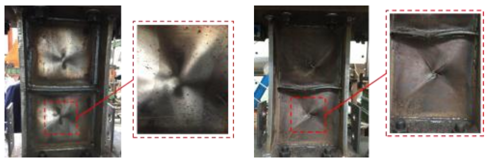
Name	Test type
A1	BMP
A2	BMP+FR（±15mm）
A3	BMP+ FR（±20mm）
B1	BMP
B2	BMP+ FR（±15mm）
B3	BMP+ FR（±20mm）

IV. TEST RESULTS AND ANALYSIS

A. *Experimental Observations*

When the displacement of the A-type damper was up to 8mm, the EDP produced more obvious external buckling deformation besides the shearing deformation in plane, and with the reciprocating loading of the displacement, the flexion surface was gradually presented as X shape. The stiffener of the damper separates the webs into two smaller sub shear plates, which makes the external buckling in the middle of the two subplates, and effectively slows the influence of the buckling deformation on the whole damper. In the whole process of reciprocating loading, the shear deformation and the hysteretic energy dissipation performance of the A-type mild steel damper were stable. The buckling deformation of specimens can be seen under loading with 30mm, but no damage occurred. The specimens A2 and A3 were subjected to fatigue loading of 15mm and 20mm respectively. The final failure modes were buckling failure in the middle of the energy dissipation sub plate. With the change of the loading direction, the buckling deformation was constantly changing with the loading direction, which eventually led to the obvious fold in the middle. As the number of loading increases, the fold deformation became more and more destructive. Fig.8 (a) shows the last failure model of specimens A3. Although the deformation of the energy dissipation plate with BLY160 is obvious, the crack was not obvious, indicating that the specimen was ductile failure.

Deformation characteristic of B-type damper was similar to that of A-type damper in the BMP test phase. In the large displacement loading stage, the energy dissipation plate generates out-of-plane buckling. During the fatigue test phase, the final failure mode of B2 was the buckling failure in the middle of the sub parts of EDB. As presented in Fig.8 (b), the X-shaped failure port appeared in the middle of the sub parts of EDB for B3, and there was a significant shedding between the stiffener and EPC. The EDP of B-type damper adopts Q235, and the deformation was obvious when breaking and the crack was large.



(a) Specimen A3 (b) Specimen B3

Figure 8. Failure mode of damper after fatigue test

B. *Basic Mechanical Properties of Damper*

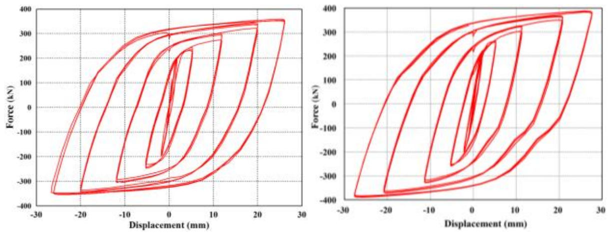
Fig. 9 shows the hysteresis curves of specimens A1 and B1. It can be seen from the figure that the hysteresis curves of the two types of dampers are full, there is no pinching phenomenon, and the initial stiffness is large. Under large displacement conditions, the damping force increases slowly. The skeleton curve is in a bifilar state as a whole, but the inflection point is not clear, and the skeleton curve can be simplified as a bifilar line according to the principle of equal energy consumption, so as to identify the parameters such as yield force and yield displacement of the damper. The parameter identification steps are as follows:

STEP 1: Extract the skeleton curve of the specimen, as shown by the solid curve of Fig. 10.

STEP 2: Straight line OC with initial slope of specimen.

STEP 3: Let point A move in the straight line of OC and connect point A with the end point of skeleton line B.

STEP 4: During the movement of point A, when the area enclosed by the double broken line OAB is equal to the area surrounded by the skeleton curve OB, the coordinates of the point A are determined, and this point is determined as the yield point of the test piece. Its abscissa is taken as the yielding displacement (D_y), and the ordinate is taken as the yield force (F_y). The ordinate of point B is the maximum force (F_{max}) of the damper; the slope of the OA section is the first stiffness (K_1), and the slope of the AB section is the second stiffness (K_2).



(a) Specimen A1 (b) Specimen B1

Figure 9. Hysteresis curve and skeleton curve of damper based on basic performance test

Fig. 11 shows the skeleton curves and basic mechanical properties of specimen A1and B1. Results of parameter identification of each specimen according to above method are given in Table V. The mechanical performance parameters of the same type damper are stable. The B-type damper adopts the Q235 steel with higher yield point, so the yield force and the maximum bearing capacity are greater than that of the A-type damper; the yield point conversion coefficient of the B-type damper is smaller than that of the A-type damper.

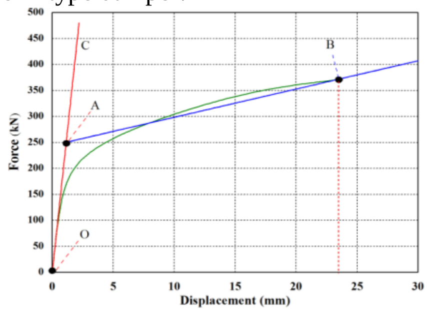
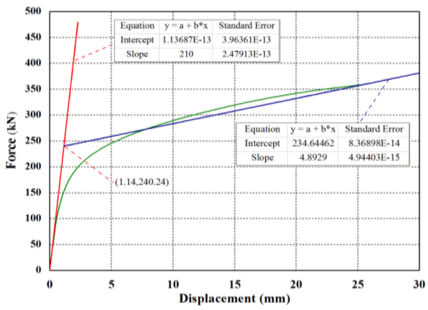
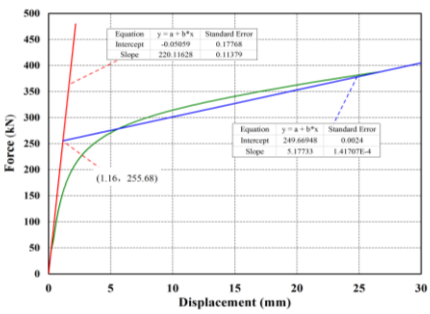


Figure 10. Parameter identification



(a) Specimen A1

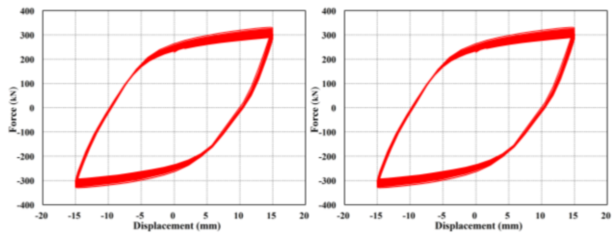


(b) Specimen B1

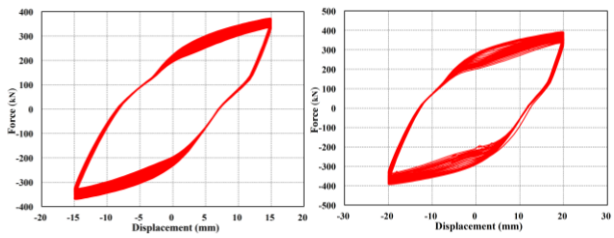
Figure 11. Skeleton curves of specimens

C. Low Cycle Fatigue Performance

Mild steel dampers should be able to withstand the repeated shearing caused by earthquakes during their lifespan. Therefore, having good fatigue resistance is an important indicator of qualified dampers. The 15% drop of maximum force was used as a condition for stopping the test, and the fatigue performance of the damper was evaluated by the number of cycles before the test stopping. Fig. 12 shows the force-displacement curves of four specimens at different amplitude displacements. It can be clearly seen from the figure that the hysteresis loop area of the four specimens gradually decreases as the number of loading cycles increases, as the EDPs gradually exhibit buckling failure with the advancing of the fatigue test, and as the plastic damage accumulates, the energy dissipation capacity decreases. Attenuation: The displacement when maximum attenuation of specimens A2 and B2 occurs is near the peak of the displacement, while that of specimens A3 and B3 is around ±5 mm. It also shows that with the increase of the loading displacement, the most serious displacement point with most serious reduction of the damping force is not at the peak displacement and approaching towards zero point.



(a) Specimen A2 (b) Specimen A3



(c) Specimen B2 (d) Specimen B3

Figure 12. Skeleton curves of specimens

Table VI shows the maximum force at the first and the 30th cycles of each specimen as well as the number of cyclic loadings of each test piece when the test was stopped. The fatigue performance of two types of dampers was close when loaded with ±15mm displacement amplitude. When the displacement amplitude reached ±20mm, the cycle loading times for the A and B dampers are 31 and 23 cycles, respectively. The fatigue performance of A-type damper using low yield point steel BLY160 as EDPs is obviously better than that of B- type damper.

TABLE V. MECHANICAL PROPERTY PARAMETERS OF DAMPER

Name	K_1 (kN/mm)	F_y (kN)	D_y (mm)	F_{max} (kN)	K_2/K_1	CCYP
A1	210.74	240.24	1.14	358.02	1/43	1.59
A2	220.41	255.68	1.16	389.61	1/43	1.60
A3	217.59	250.23	1.15	370.08	1/40	1.60
Mean	216.25	248.72	1.15	372.56	1/42	1.59
B1	204.77	292.27	1.43	399.12	1/48	1.22
B2	203.14	290.16	1.43	396.83	1/43	1.21
B3	205.00	291.90	1.42	399.41	1/40	1.21
Mean	204.30	291.44	1.43	398.45	1/43	1.21

TABLE VI. RESULTS OF FATIGUE PERFORMANCE

Name	Amplitude (mm)	F_{max} (kN)		N_f
		1th cycle	30th cycle	
A2	-15	325.48	290.71	43
	+15	330.93	297.31	
A3	-20	350.62	298.11	31
	+20	354.91	317.75	
B2	-15	472.33	419.65	43
	+15	470.14	428.64	
B3	-20	350.62	—	23
	+20	354.91	—	

V. CONCLUSION

(1) The shear-type damper using domestic mild steel as energy dissipation material is simple in structure, convenient in processing, and has a full hysteresis curve. It can effectively absorb seismic energy in the engineering structure.

(2) The skeleton curves of the two types of dampers can be simplified to two-fold line models according to the principle of equal energy dissipation, and the performance parameters such as the yield force and the yield displacement are determined according to the position of the inflection point.

(3) Under the low-cycle fatigue loading of ±20mm displacement amplitude, the maximum bearing capacity of the A-type damper at the 31st single cycle is reduced by 15%. The B-type damper is only cyclically loaded 23 times when the test was stopped. The fatigue performance of the damper using mild steel BLY160 is significantly better than that of the damper using Q235.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Shuguang Wang and Weiqing Liu defined the research theme; Weizhi Xu carried out the experiment and interpreted the results; Weizhi Xu wrote the paper; Shuguang Wang and Dongsheng Du checked and revised the paper; all authors had approved the final version

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