Experiment Investigation and Numerical Analysis on the Low-yield-point Steel Shear Panel Dampers

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ABSTRACT

Pseudo-static test of two groups of mild steel shear panel dampers (MSSPD) made of LYP160 steel were carried out for study of the mechanical properties, low cycle fatigue behavior and earthquake mitigation effect. Four groups of the loading history were applied to trace the hardening of the shear panels. The influences of web plate size and width-thickness ratio and the cyclical load amplitude were analyzed. The entity model was built by ANSYS with both geometric and material nonlinear analysis included in modeling. The combined hardening material model of Chaboche kinematic hardening rule and Voce isotropic hardening rule was adopt to simulate the cyclic hardening of LYP160 steel. The result shows that MSSPD has the features of large initial stiffness, high ultimate bearing capacity, favorable ductility and excellent energy dissipation capacity. The mechanic parameters are influenced by the sizes of the shear panel and the amplitude of the load history. Simulated hysteresis loops predicted by combined hardening model agree well with test results, especially reflecting the cyclic hardening character of low-yield-point steel.

INTRODUCTION

Structural control is widely developed in the design for resisting wind and earthquake loading. Hysteresis damper is effective passive control device by improving the serviceability and ultimate resisting capacity (Housner et al. 1997). In Japan, it is noticed that low-yield strength (LYP) steel is suitable for an energy-dissipating member, which has the character of favorable ductility performance and adaptability to steel structures (Akiyama, H. 1985). Test and simulation analysis are conducted by previous work during a long period (Nakashima et al. 1995; Zhang, C et al. 2012), some material models are proposed (Armstrong et al.1966,Chaboche et al.1979; Ohno et al. 1993). This paper focuses on the hysteresis properties, low cycle fatigue behavior and energy dissipation of LYP160 steel, the combine hardening model is adopted by numeric analysis to simulate the character of cyclic hardening.

SPECIMEN AND TEST SETUP

Specimen design. The shape and size of the shear panel dampers are shown in Figure 1, The specimen consists of a shear plane made of a low-yield-point steel (designated as LYP 160 in this paper) and two flanges (made of Q235, equivalent to SS400) that confined the shear panel. The thick boards on the bottom and top are considered to be rigid, linking the two same shear panel together and connecting the specimen to the loading equipment. The specimens are divided into two types by the size, which are labeled as RT400 and RT600.

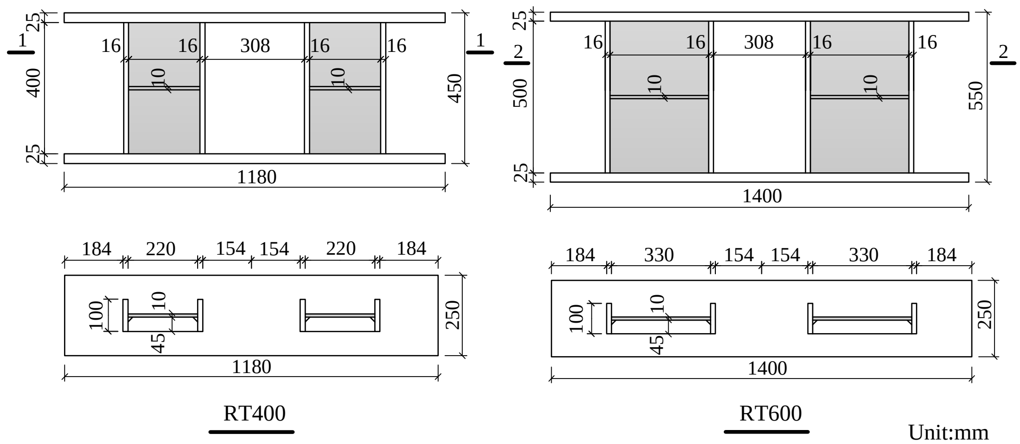

Figure 1. Design sketch of Specimen

Test setup. Figure 2 shows the loading setup employed in the test, the specimen are fixed between the top and bottom beam. One head of the 200t MTS dynamic actuator is fixed on the back strength wall and another head is connected with the top beam that can move horizontally.

In this experiment, force is measured through the actuator load cell and the displacement is measured through the transducer located in the each side of the top board, which can detect the horizontal displacement and torsion of the top board relative to the bottom board.

Figure 2. Test setup

Test plan

The damper is expected to absorb the seismic energy cyclically. The hysteretic incremental quasi-static loading is set for the test. Four groups of the loading history are applied to the specimens. The loading process works in displacement-control mode, the history of the relative horizontal displacement is shown in Figure 3.

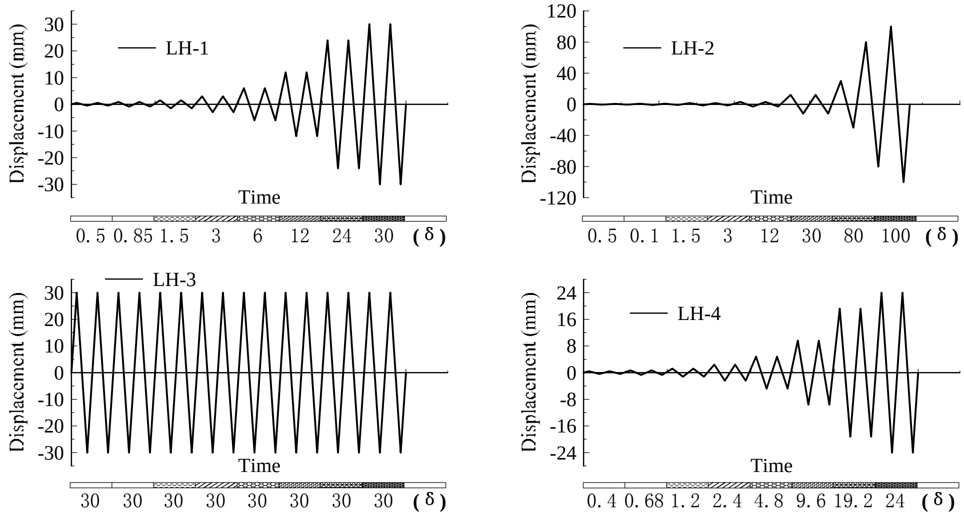

Figure 3. Hysteretic loading history

The MSSPD typed into RT-400 are fabricated four identical specimens for the four different loading schemes to observe the influence of the loading history on dampers' hysteretic behavior. Two specimens of type RT-600 are experience the loading history of LH-1 and LH-2. The number of the specimen is list in the Table 1.During the test, loading is terminated when the horizontal force decreased to 85% of the maximum or fatal crack appeared.

Table 1. Specimen number

Types	RT400				RT600	
Specimen Number	A1	A2	A3	A4	B1	B2
Loading history	LH-1	LH-2	LH-3	LH-4	LH-1	LH-2

TEST RESULT AND DISCUSSION

Hysteretic characteristic. The horizontal force versus displacement relationship can well reflect the hysteretic performance of the damper. Figure 4 shows the force-displacement curves of the specimens. It can be concluded that the hysteretic curves are plump with ideal ductility and energy dissipative capacity. MSSPD of type RT600 shows high strength and stiffness with preferable ductility and seismic behavior compared with the type RT400.

Figure 5 shows the skeleton curve of specimens, it is a shape of converse Z type existing four stages named elastic, yield, hardening and stable phase. The basic mechanical parameters can be inferred from the hysteretic curve by graphing method, the details are shown as Table 2.

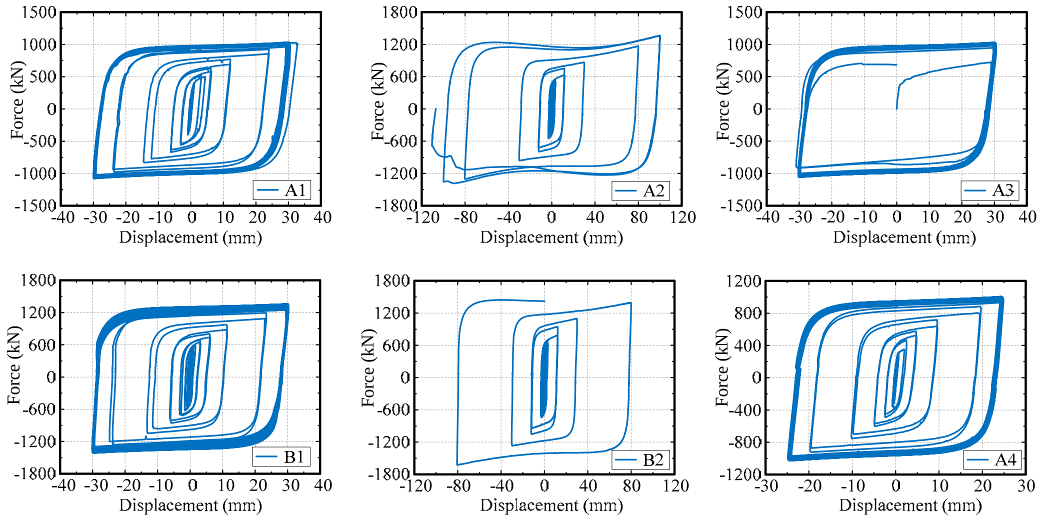

Figure 4. Force-displacement hysteretic curves

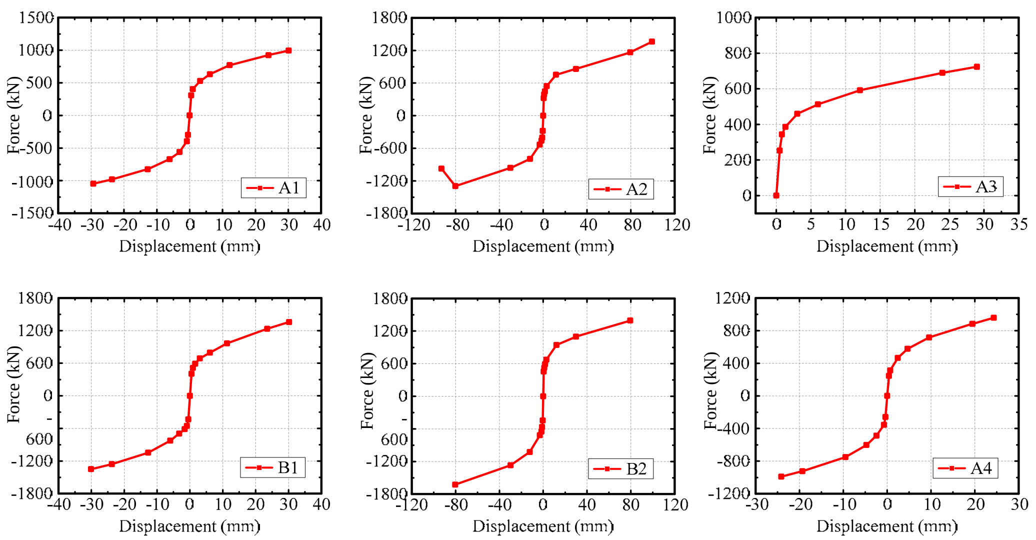

Figure 5. Force-displacement skeleton curves

Table 2. Mechanical parameter

No.	Yield force F_y(kN)	Yield displacement D_y(mm)	Initial stiffness k_1(kN/mm)	Post-yield stiffness k_2(kN/mm)	Maximum displacement D_{max} (mm)	Maximum Force F_{max}(kN)
A1	394	0.75	525.3	34.5	29.71	1058
A2	421	0.68	619.1	38.3	100.05	1373
B1	566	0.67	844.8	39.2	29.76	1386
B2	557	0.61	913.1	34.6	80.35	1387

Fatigue characteristic. Fatigue performance is concerned in this part, the test photos are shown in Fig.6.

Fig.6. Failure mode

During the experiment, the specimens suffered the horizontal loading with small maximum displacement amplitude crack along the welding line between the web and the stiffener. The failure mode of the specimens loaded under large displacement cycle is flange crack. For the specimen of type RT600 with width-thickness ratio larger than 30, the out-of-plane shear buckling can be observed under the static cyclical loading with lager displacement amplitude. The details of the low cycle fatigue properties are shown as Table 3.

Table 3. Fatigue performance

No.	Load history	Maximum displacement (mm)	Maximum drift angle γ_{max}	Cycles	Failure mode
A1	LH-1	30	0.075	27	Web crack along stiffener
A2	LH-2	100	0.250	2	Flange root crack
A3	LH-3	30	0.075	27	Web crack along stiffener
A4	LH-4	24	0.060	34	Web crack along stiffener
B1	LH-1	30	0.060	35	Web buckling, corner crack
B2	LH-2	80	0.200	1	No damage phenomenon

Energy-dissipating capacity analysis. Based on the force-displacement hysteretic curves of the specimen, the energy dissipation per cycle and the equivalent damping ratio can be quantitatively calculated to estimate the seismic performance of the damper. The energy dissipation per cycle (ED), accumulated energy dissipation (AED) and the equivalent damping ratio (*he*) of the specimen are compared in Figure 7, specimens of type RT600 behave better than RT400 in energy dissipation.

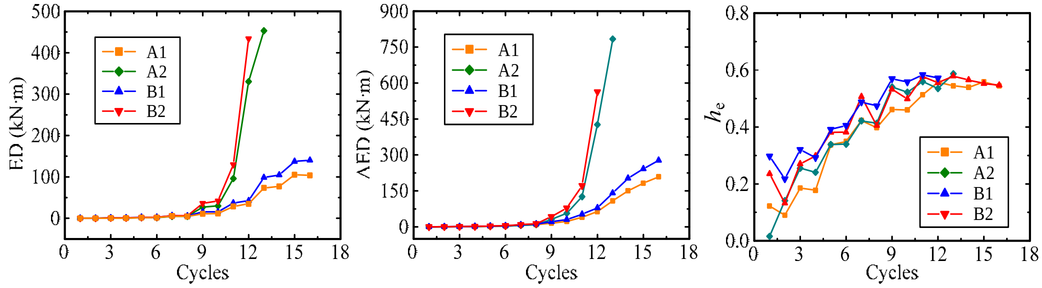

Figure 7. Energy dissipation capacity

NUMERIC ANALYSIS

Finite element modelling. The numerical model of the specimen is built by the general-purpose Finite Element Analysis program, ANSYS 13.0. A four-node doubly curved, full-integration quadrilateral shell element (shell 181) is employed for this analysis. Considering the top and bottom ends of the shear panel are connected to the considerably rigid board in practice, both ends of the numerical model are constrained by a rigid surface and the degree of freedom are fixed except for displacement in the *x* and *z* direction. The nonlinear analysis is included in the model by adopting the option 'NlGEOM' available.

Combined hardening model. A appropriate material model is a prerequisite to obtain accurate prediction from a finite element model, especially for the MSSPD made of the low-yield-point steel (LYP160), which has the future of long yield phase and cyclical hardening. Chaboche and his assistant (1979) proposed a 'decomposed' nonlinear kinematic hardening rule in the following form.

$$d\alpha = \sum_{i=1}^{M} d\alpha_i, d\alpha_i = \frac{2}{3}C_i d\varepsilon^{pl} - \gamma_i \alpha_i d\varepsilon^{pl} \tag{1}$$

The Chaboche decomposed model divide the hysteresis curve into some critical segments and each of these decomposed rules has its specific purpose (Bari,S. 2000). Chaboche (1986) proposed to use three decomposed hardening rules, M=3 in equation 1 to improve the simulation of the simulation the hysteresis loop. They suggested that the first rule should start hardening with a very large modulus and stabilizes very quickly. The second rule should simulate the transient nonlinear portion of the stable hysteresis curve. Finally, the third rule should be a linear hardening rule to represent the subsequent linear part of the hysteresis curve at a high strain range.

The theory of the model is adopt by the FE program ANSYS and the kinematic hardening rule can be combined with nonlinear isotropic hardening for tracing the material hardening progress (ANSYS, 2008). The nonlinear isotropic hardening rule adopt by ANSYS is based on Voce model (1955) with the form as following. It can reflect the expand of elastic zone with the plastic strain accumulated.

$$\sigma = k + R_0 \varepsilon^{pl} + R_\infty (1 - e^{-b\varepsilon^{pl}}) \tag{2}$$

The parameters determined following this method and used for simulation by the combined hardening model are:

$$\sigma_0 = 160Mpa, E = 20600Mpa$$

$$C_{1-3} = 20000, 6000, 550; \gamma_{1-3} = 20000, 180, 9$$

$$k = 160, R_0 = 0, R_\infty = 155, b = 3$$

Comparisons between the experimental hysteresis loop and results predicted by combined model are shown as Figure 8. Combined hardening model of Chaboche decomposed rule and nonlinear isotropic rule correlates well with the hysteretic performance of the specimen.

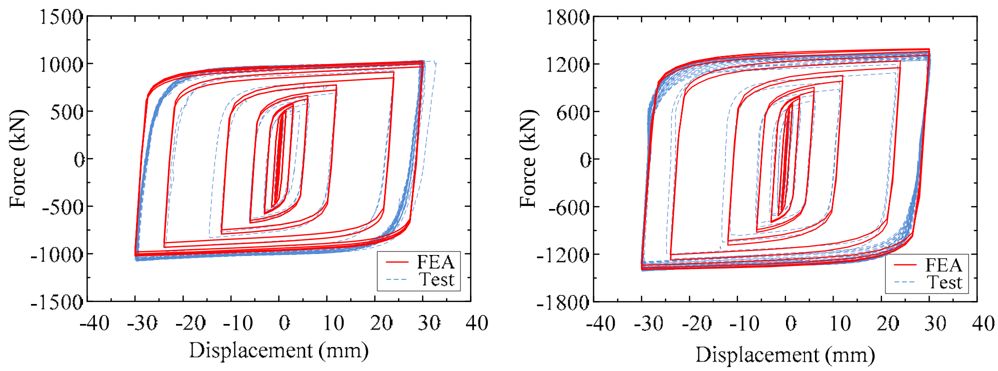

Figure 8. Comparison of test and FE analysis on hysteretic loops

CONCLUSION

This paper presents an experimental study examining the hysteretic behavior of shear panels made of a low yield steel LYP 160, the influences of the loading history and width-to-thickness ratio are studied by different specimens. Numerical analysis model is generated by ANSYS, the nonlinear combined hardening model are adopt to simulate the significant hardening. Concluding remarks are obtained as follows.

(1) MSSPD made of steel of LYP160 and SS400 has good hysteretic performance with large initial stiffness, small yield displacement, ideal ductility and favorable energy dissipation capacity.

(2) A reasonable width-thickness ratio is important for the stable hysteresis loop, the ratio less than 20 makes the shear panel too rigid to deform compatibly with the flange, one larger than 35 leads to the bulking.

(3) The cycles under maximum displacement is determined by the constant drift angle amplitude, less related to the loading history with small deformation.

(4) Combined hardening model of Chaboche kinematic hardening rule and Voce isotropic hardening rule is suitable for simulating the hysteresis of the shear panel damper, especially for tracing the hardening progress of the low-yield-point steel.

ACKNOWLEDGEMENT

The writers gratefully acknowledge the financial support provided by the National Science Fund of China (51138007), the National Science & Technology Support Program of China (2011BAJ09B01), and the National Science & Technology Support Program of China (2011BAJ09B02).

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