Study of an innovative graded metal damper

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ABSTRACT

Metal dampers are often installed in building structures to reduce the seismic response of structures. However, there exist some issues to be solved in practical engineering. For one thing, metal damper cannot dissipate the seismic energy in frequent earthquakes if it is designed to yield in moderate or rare earthquakes. For another, metal damper cannot afford large stiffness and load carrying capacity in moderate or rare earthquakes if it is designed to yield in frequent earthquakes. This paper proposes an innovative damper which has two yield points to satisfy the different seismic performance demands under different earthquake intensities. In this study, low cycle reversed loading tests were conducted on five annular metal dampers. The hysteresis behaviors of annular metal dampers were investigated according to the experimental results and theoretical analyses. The research results show that annular metal damper possesses excellent deformation and energy dissipation capacity. Two graded yield metal dampers were tested by quasi-static cyclic loading. A case study is conducted to compare the seismic response of conventional reinforced concrete moment-resisting frame structure with that of the structure installed with the graded yield metal dampers under three levels of earthquakes using SAP2000. The results indicate that the graded yield metal damper has two yield points and can be used to reduce the responses of the structure under earthquakes of different intensities.

Keywords: metal damper; restoring force model; graded yield; seismic performance; hysteresis curve; numerical simulation

1. INTRODUCTION

The traditional seismic design method mainly relies on plastic deformation of building structures to dissipate the seismic energy and prevent the collapse of structures. Therefore, the traditional seismic structures have inevitably been damaged or destroyed after strong earthquakes [1, 2]. In the early 1970s, energy dissipation and damping technology was introduced into the field of earthquake engineering [3, 4]. The key innovation of energy dissipation and damping technology is to set up damper in specific parts of building structures [5, 6]. Metal damper is a kind of energy dissipating device which dissipate seismic energy by the plastic hysteresis deformation of metal material. Metal damper has been widely used in practical engineering due to its simple mechanical model, stable mechanical properties and low production maintenance cost [7].

Kelly et al. first put forward the concept of "passive control technology” in 1972 and developed a number of different configuration forms of metal dampers to dissipate seismic energy, U-shaped metal damper is the representative invention of these device [8]. Since then, scholars at home and abroad have developed a large number of dampers based on different energy dissipation concepts and configuration forms. Whittaker et al. proposed X-shaped stiffened steel plate damper and carried out shaking table test on the damper. The test results show that X-shaped stiffened steel plate damper can dissipate 70% seismic input energy and possesses good hysteretic performance [9]. Yasushi Kurokawa et al. developed a kind of honeycomb-shaped metal damper and conducted low cycle reversed loading test on it. The experimental results validates that the damper has excellent energy dissipation capacity and the test hysteresis curves are full spindles-shaped [10]. Kazuaki et al. proposed a kind of damper which consists of U-shaped steel plate and rubber bearing for isolation design, and carried out load test on the dampers with different parameters which include loading amplitude and temperature [11].

However, conventional metal dampers only possess one yield point, and it can be designed to yield under the earthquake of single intensity. To protect the structure under multiple levels of earthquakes more efficiently by using the metal dampers, a few researchers developed new dampers with multi-yield points in recent years. Sun et al. developed an assembled steel double-stage yield BRB and conducted a series of theoretical analyses and experimental researches [12]. Moreover, Barbagallo et al. proposed a more effective concentric braced frame installed with the double-stage yield BRB and verified the seismic performance of the novel concentric braced frame by finite element simulation [13]. Li et al. conducted experimental and theoretical studies on a two-level-yielding steel coupling beam which can be applied for improving seismic resistance of shear wall system [14]. This paper proposes an innovative damper which has two yield points to satisfy the different seismic performance demands under different earthquake intensities and a series of experimental and theoretical analyses are carried out.

2. TESTS ON ANNULAR METAL DAMPER

2.1 configuration forms and working principle

The annular metal damper is made by cutting and welding the steel plate, and it consists of four parts which include arc segments, straight segments, transition segments and connection plates. The energy dissipation capacity of the metal damper is mainly determined by the design of arc segments and straight segments. The transition segments are applied to prevent the stress concentration when the damper is subjected to the action of external loading. The screw holes in the connection plates are used to connect the damper to other structural components.

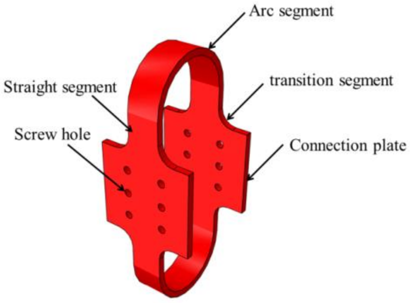


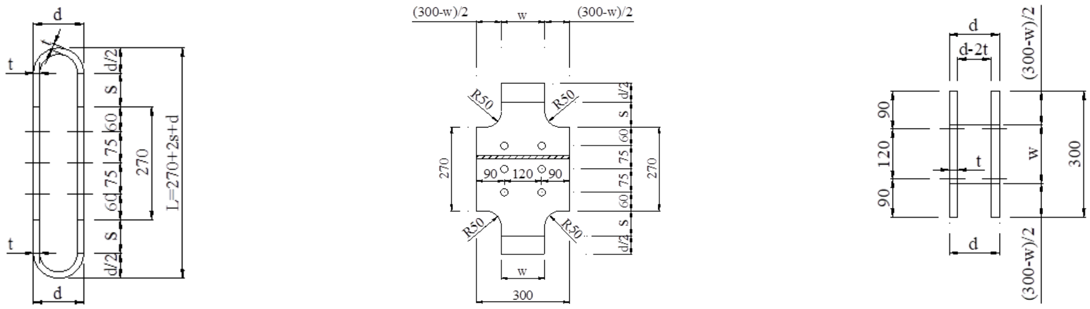
Fig.1. Configuration of annular metal damper

2.2 Design of the test specimen

To evaluate the seismic performance of annular metal damper, five specimens were tested by low cycle reversed loading. The dimensions of specimens are shown in Table 1. The geometry configurations of specimens are shown in Fig. 2.

Table 1 Dimensions of specimens (unit: mm)

Specimen No.	t	w	d	s	L
LS-1	18	100	282	120	810
LS-2	20	100	280	120	810
LS-3	20	140	280	120	810
LS-4	20	100	240	120	770
LS-5	20	140	280	80	730



(a) Front view (b) Side view (c) Top view

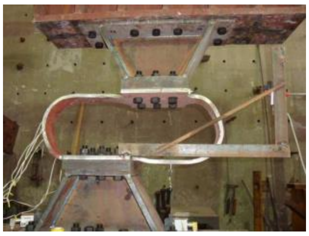
Fig.2. Geometry configurations of specimens (unit: mm)

2.3 Test results

2.3.1 Failure modes

(a) Initial crack (180mm)

(b) The crack of arc segment (192mm)



(c) Deformation mode (228mm)

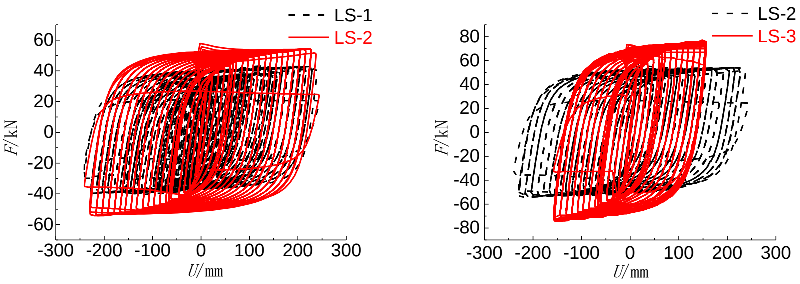
(d) Failure mode (240mm)

Fig.3. Loading process of LS-1

The deformation mode and crack development of specimen LS-1 were presented in Fig.4, the initial crack was observed at the transitional region of the lower left when the loading displacement amplitude reached up to 180mm, this crack developed and propagated with the increase of loading displacement. The crack of arc segment initiated in the amplitude of 192mm. It can be seen from Fig. 3(c) that rolling flexure deformation is the main deformation mechanism of annular metal damper. The fracture of specimen LS-1 occurred at the transition segment of the upper right when the loading amplitude reaches 240mm.

2.3.2 Hysteresis curves

The hysteretic curves of all specimens are shown in Fig.5, the hysteretic curves of each specimen are full spindle-shaped in the loading process, the bearing capacity and energy dissipation capacity did not decrease before the loading amplitude reached up to design displacement. It also can be concluded that the deformation and energy dissipation capability of annular metal damper is excellent from Fig.4.



(a) (b)

Fig.4. Hysteresis curves

3 TESTS ON GRADED YIELD METAL DAMPER

3.1 configuration forms and working principle

This paper proposes an innovative graded yield metal damper and it consists of two parts which are named as inner ring and outer ring, respectively, as shown in Fig.5. According to the proposed calculation formulae, inner ring can be designed to yield in frequent earthquakes and outer ring can be designed to yield in moderates earthquakes. Alternatively, inner ring can be also designed to yield in moderate earthquakes and outer ring can be also designed to yield in rare earthquakes. The graded metal damper can satisfy the different seismic performance demands of building structures under different earthquake intensities.

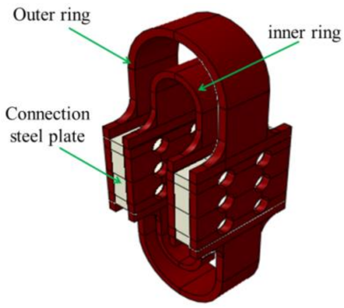


Fig.5. Configuration of graded yield metal damper

3.2 Design of the test specimen

In this study, inner ring is designed to yield under frequent earthquakes and outer ring is designed to yield under moderate earthquakes. Two specimens of the graded yield metal dampers, named as A and B, were manufactured in this test. The dimensions of the specimens are shown in Table 2.

Table 2 Dimensions of specimens (unit: mm)

Specimen No.	Size	t	w	d	s	L
A	Outer ring	22	130	278	140	850
	Inner ring	18	130	142	100	630
B	Outer ring	20	120	260	120	790
	Inner ring	18	120	142	80	590

3.3 Test results

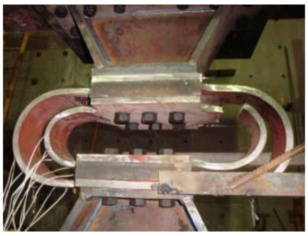
3.3.1 Failure modes

The deformation mode and crack development of specimen B were presented in Fig.6, the initial crack was observed at the transitional region of the upper right of inner ring when the loading displacement amplitude reached up to 48mm, this crack developed and propagated with the increase of loading displacement. The first crack of outer ring initiated at the lower left of arc segment in the amplitude of 66mm. It can be seen from Fig. 6(d) that the fracture of specimen A occurred at the transition segment of the upper right of inner ring when the loading amplitude reaches 96mm.

(a) Initial crack of inner ring (48mm)

(b) Initial crack of outer ring (66mm)

(c) Crack development of inner ring (84mm)

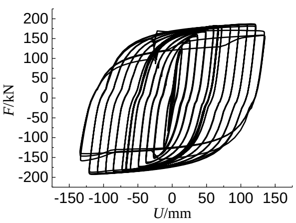


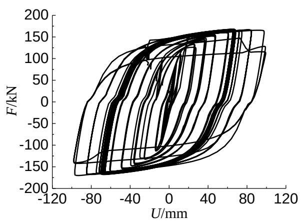
(d) Failure mode (96mm)

Fig.6. Loading process of Specimen B

3.3.2 Hysteresis curves

The hysteretic curves of the graded yield metal damper are shown in Fig.13, the hysteretic curves of each specimen are full spindle-shaped in the loading process, the bearing capacity and energy dissipation capacity did not decrease before the loading amplitude reached up to design displacement. It also can be concluded that the deformation and energy dissipation capability of grade yield metal damper is excellent from Fig.7.





(a) Specimen A (b) Specimen B

Fig.7. Hysteresis curves of graded yield metal damper

4. CASE STUDY

4.1 Description of the structure

The project of case study is located in Haikou, Hainan Province. Seismic fortification intensity is 8, and design basic seismic acceleration peak value is 0.3g. The number of floors is 3 and the height of the building structure is 11.8m. Two analysis models was established using SAP2000 software. The original structure model is named as uncontrolled model, and the structure model installed with graded yield metal dampers is named as controlled model. Simulation analysis model is shown in Fig.8. According to Chinese Code for Seismic Design of Buildings (GB50011-2010), seven sets of earthquake records (5natural waves and 2 artificial waves) are selected as the input ground motions. In the following researches, the results of inter-story drift ratio and top displacement are the average values under seven earthquake ground waves. The acceleration time history curves of seven input earthquake waves are shown in Fig.9.

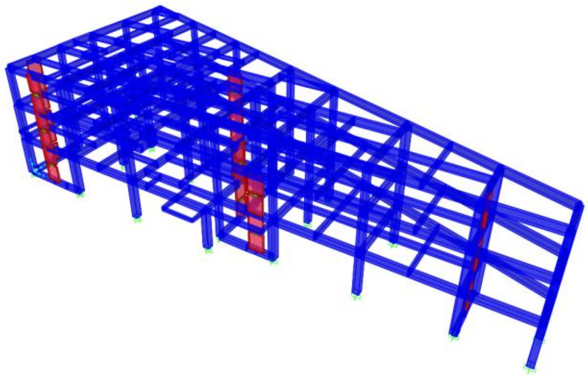


Fig.8. Numerical model

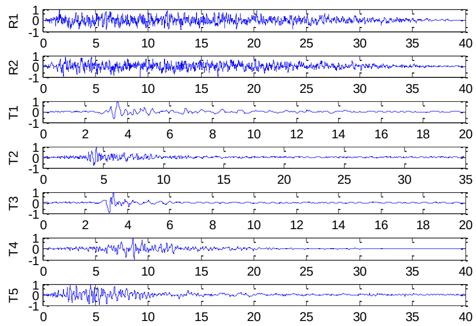
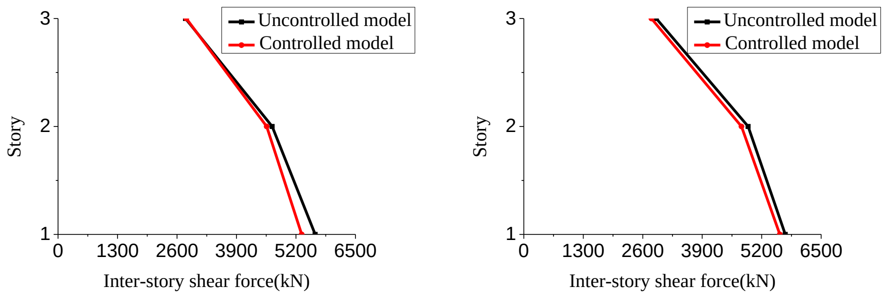


Fig.9. Acceleration time history curves

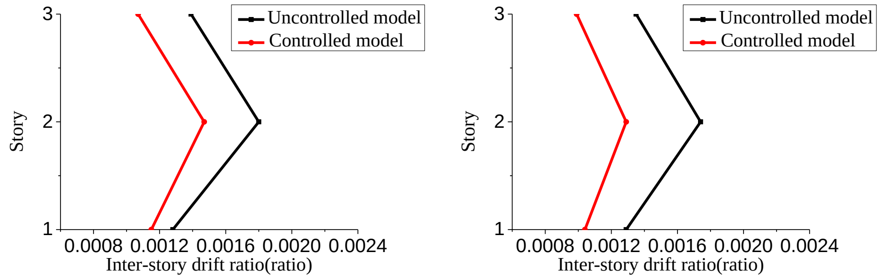
4.2 Response under frequent earthquakes

As shown in Fig.10, the inter-story shear force of controlled model is lower than that of uncontrolled model in the first story, another two stories is basically some. It can be also demonstrated from Fig.11 that controlled model are more effective in the control of inter-story drift ratio compare with uncontrolled model. Fig.12 shows the inner ring yields and the outer ring of graded yield metal damper remain in elastic under frequent earthquakes.



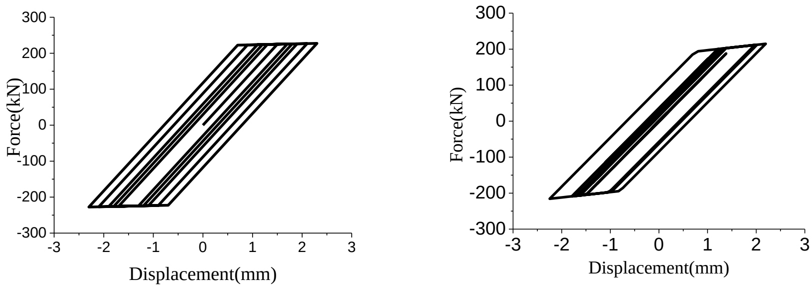
(a) X direction (b) Y direction

Fig.10. Inter-story shear force curves under frequent earthquakes



(a) X direction (b) Y direction

Fig.11. Inter-story drift ratio curves under frequent earthquakes

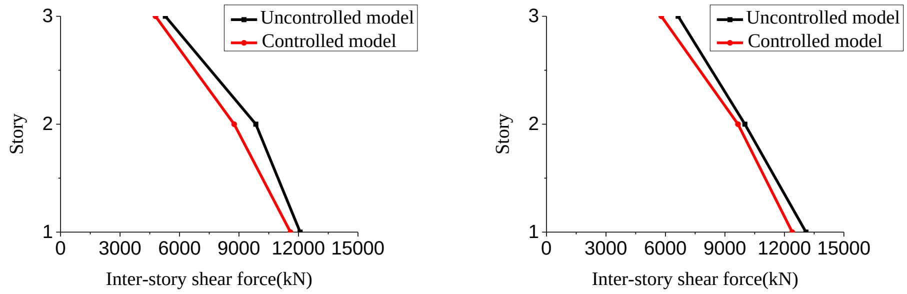


(a) X direction (b) Y direction

Fig.12. Hysteresis curves of damper under frequent earthquakes

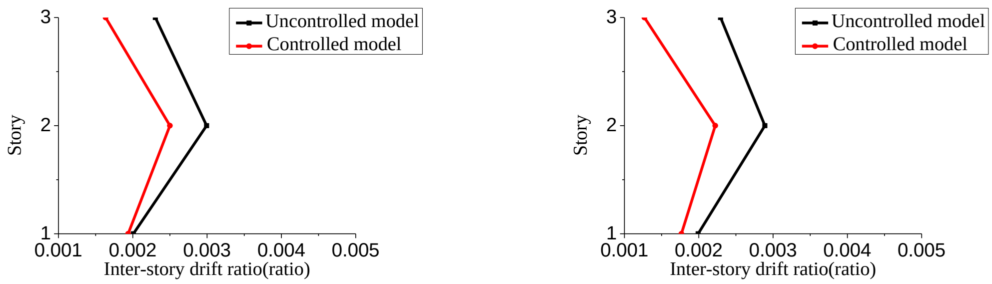
4.3 Response under moderate earthquakes

It can be seen from Fig.13 that the control effect of graded yield metal dampers in inter-story shear force improves a little. Graded yield metal dampers reduce the seismic displacement response of the structure significantly under moderate earthquakes which can be concluded from Fig.14. As seen in Fig.15, the inner ring and the outer ring of graded yield metal damper all yields under moderate earthquakes.



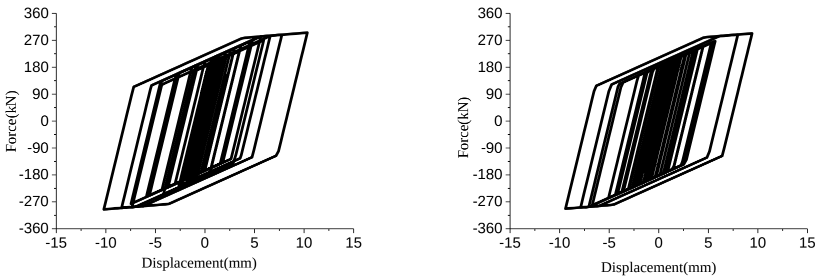
(a) X direction (b) Y direction

Fig.13. Inter-story shear force curves under moderate earthquakes



(a) X direction (b) Y direction

Fig.14. Inter-story drift ratio curves under moderate earthquakes

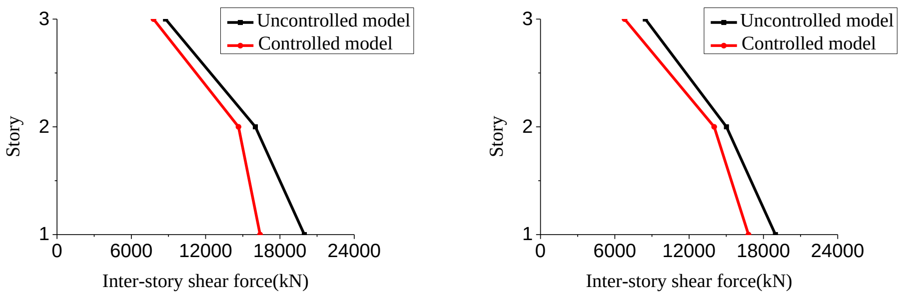


(a) X direction (b) Y direction

Fig.15. Hysteresis curves of damper under moderate earthquakes

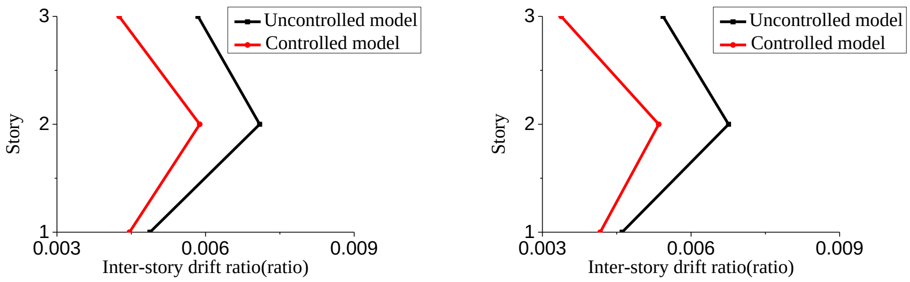
4.4 Response under rare earthquakes

The comparisons of the maximum inter-story shear force and drift ratio of two structure models under rare earthquakes are shown in Fig.16 and Fig.17, respectively. The responses of controlled model are smaller compare with the responses of uncontrolled model, which indicates the seismic performance of the structure is improved by installing graded yield metal dampers. Fig.18 shows the force-displacement hysteresis curves of the damper and it can be observed that grade yield metal damper has two yield points and energy dissipation capacity is excellent.



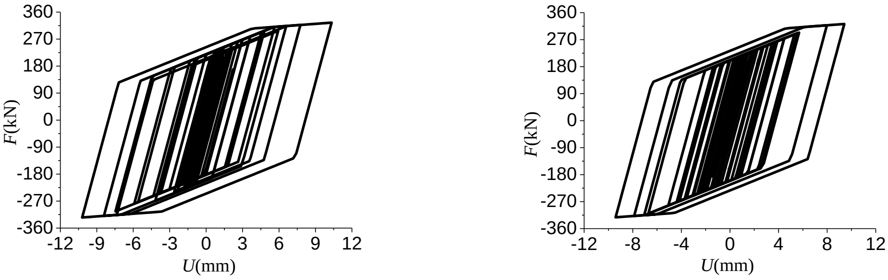
(a) X direction (b) Y direction

Fig.16. Inter-story shear force curves under rare earthquakes



(a) X direction (b) Y direction

Fig.17. Inter-story drift ratio curves under rare earthquakes



(a) X direction (b) Y direction

Fig.18. Hysteresis curves of damper under rare earthquakes

5. CONCLUSIONS

A new type of metal damper, graded yield metal damper possessing two yield points, is proposed in this study. The following conclusions can be drawn from the above work:

(1) From the test results, it can be concluded that annular metal damper possesses excellent deformation and energy dissipation capacity.

(2) Based on the experimental study and numerical analysis, under small earthquakes, inner ring of the damper yields first, outer ring remains elastic, and the damper provides additional damping and additional stiffness for the structure. Under moderate earthquakes, outer ring of the damper yields and dissipates the seismic energy with inner ring together.

(3) The case study indicates that the new damper can be used to mitigate the responses as well as the damage of the building structure efficiently under multiple levels of earthquakes, including frequent earthquakes, moderate earthquakes, and rare earthquakes.

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