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AN EXPERIMENTAL STUDY OF IN-PLANE, ARCH-SHAPED FLEXURAL DAMPER

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An innovative displacement-dependent metallic yielding damper designed to deform inelastically under in-plane flexural bending for seismic protection of building structures is proposed. The in-plane flexural damper that originated from a portal frame is modified by replacing the beam with a circular arch so that the effect of stress concentration can be minimized. Component tests of the in-plane dampers were conducted and compared with analytical results. Hysteresis of the component test indicates a consistent energy-dissipative characteristic of the damper. Moreover, seismic performance of the proposed damper via a series of shaking table tests was carried out. Excellent seismic performance of the proposed in-plane arched damper was observed. The acceleration responses in both peak and root-mean-squares of all floors are significantly reduced, and were greater in extent compared to the earthquake intensity increases.

Keywords: Metallic damper, Seismic, Inelastic, Circular arch.

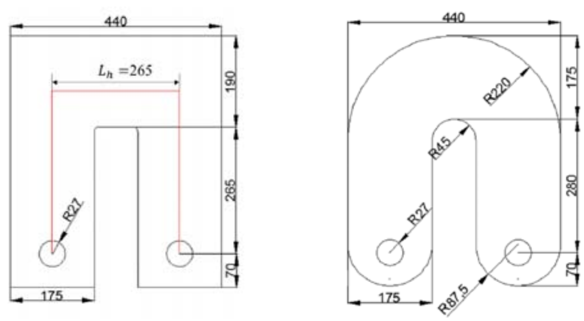
1 INTRODUCTION

Seismic energy-dissipative dampers have been widely adopted for earthquake-protection of building structures. Metallic yielding dampers such as ADAS (Whittaker et al, 1991), TADAS (Tsai et al. 1993) or Pre-bent stripe (Wang et al. 2009) that utilize the strength and ductility of steel plates are alternatives considered to be cost-effective among others. The aforementioned metallic dampers in common are designed to deform in an out-of-plane flexural mode by resisting the loading in their weak axis without economical concerns. As an effort to improve the efficiency of material utilization, seismic structural dampers designed to bend in an in-plane flexural mode by the strong axis of the steel plates have attracted serious attentions recently. The steel slit damper (SSD) proposed by Chan and Albermani (2006) and the E-shaped energy-dissipation bearing (EDB) by Guan et al (2010) are typical in-plane flexural dampers. Component test conducted by Chan and Albermani (2006) indicates that the SSD fails in groove tearing-off at the ends of the segments during a cyclic loading test. The ultimate strength of the specimen appears to be about 3-ton which is insufficient for practical use. The EDB on the other hand is developed for energy-dissipation of seismic isolation bearings of a long-span bridge. Park and Lee (2012) propose a portal-frame-shaped steel damper of which the horizontal portion is divided into parallel segments by a couple of slits to reduce the effect of shear deformation. T-shaped brackets are introduced to prevent lateral instability. Test results show that local buckling occurs inevitably even if laterally reinforced. This limits the capacity of the damper in both strength and deformation and requires further improvement for practical use.

A new type of metallic damper referred to as the in-plane arched damper is presented in this paper. With a similar concept, the proposed device differs from the portal-frame counterpart by replacing the horizontal portion of the frame with a circular arch so as to minimize the effect of stress concentration that may result in failure of the damper in an early stage. Circular arch is chosen since the curve beam theory from elasticity can be readily adopted for analysis. With this design modification, the damper increases both its strength and ductility without lateral reinforcement while inheriting the merit of an in-plane flexural damper. Component tests of the in-plane dampers in both portal frame and arched shapes have been conducted and compared with each other. Hysteresis from the component tests indicates consistent energy-dissipative characteristics of the dampers with significant performance improvement for the arched version. Moreover, seismic performance of the proposed in-plane arched damper via a series of shaking table tests has been carried out. Encouraging seismic performance of the proposed in-plane arched damper has been observed.

2 COMPONENT TESTS

For the purpose of comparison, in-plane flexural dampers in forms of both the portal frame and arched-shape are fabricated for the component tests. Both dampers consist of a pair of identical plates (25mm in thickness) with a straight or curved beam and perpendicular arms as illustrated in Figure 3. The initial stiffness are 67.9 kN/mm for the portal frame and 71.1 kN/mm for the arched damper estimated using the theories of mechanics of materials (Boresi et al. 1993) and elasticity (Timoshenko and Goodier 1970). The details of the derivation can be found in Wang (2014). The dampers are expected to have a loading capacity and ultimate displacement of at least 500 kN and 30 mm, respectively, as desired by practical use.

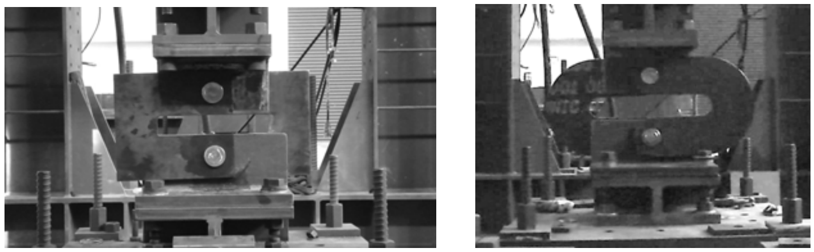


unit: mm

(a) Portal frame. (b) Arched-shape.

Figure 1. Design of the in-plane flexural dampers for component tests.

The dampers are connected with pins through fixtures to the actuator in one end and to the ground in the other, as shown in Figure 2. Cyclic loading with amplitudes of 10mm, 15mm, 20 mm, 25 mm, 30 mm and 35 mm repeated 5 cycles each have been conducted at a loading rate of 0.05 Hz. The portal frame fails early, however, at the amplitude of 20mm by cracking at the inner corners due to stress concentration.



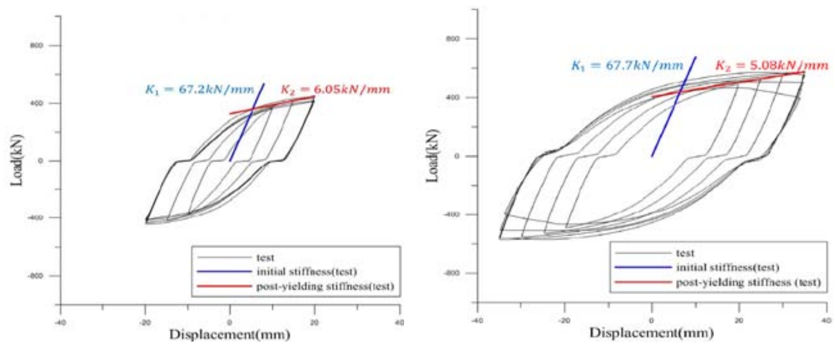
(a) Portal frame. (b) Arched-shape.

Figure 2. Experimental setup for component tests.

The test results are presented in form of hysteresis as illustrated in Figure 3. It is observed for the arched one that the hysteretic loops of all amplitudes but the 35 mm follow the same track closely in the corresponding repeated process. The hysteresis for 35 mm degrades, however, from cycle to cycle in both stiffness and enclosing area due to damage resulting from warping deformation. The damper reaches its ultimate strength of 570.9 kN for the first cycle before deteriorates. The initial stiffness of the arched damper reads K_1=67.7 *kN/mm* with approximately 5% difference from the theoretical value of 71.1 kN/mm. The post-yielding stiffness K_2=5.08 *kN/mm* is determined by connecting the maximum forces corresponding to various loading amplitudes which constitutes a post-yielding stiffness ratio（$\alpha = K_1/ K_2$）of 0.075. These parameters are used to represent a bi-linear model for numerical analysis. The effective yielding strength, P_y^{eff}=437*kN*, and the effective yielding displacement, Δ_y^{eff} = 6.45mm, are defined as the coordinates at the intersection of the two slopes. The overall ductility of the damper is then determined by $\mu=\Delta_u/\Delta_y^{eff}$=5.4. The ultimate strength of the portal frame, on the other hand, reads only 443.5kN (cf. 570.9 kN) with the ductility calculated to be μ=3.7（cf. 5.4）. A significant improvement has been obtained with a slight modification in the shape of the steel plates. It is noted that a displacement setback of the hysteretic loops at the neutral position of the loading of about 3mm is observed due to the gap between the pin and the drilled hole in the plates. This can be improved by replacing the pin connections with fixed ends, as will be considered in subsequent studies.

3 SEISMIC PERFORMANCE TESTS

A series of shaking table tests on a five-story model frame has been conducted to assess the effectiveness of using the proposed in-plane arched damper for seismic vibration control. The bottom three stories of the model are implemented with dampers via diagonal bracings on both sides of the frame parallel to the excitation direction of the table. To explore the seismic performance of the damper, the 1940 El Centro earthquake is considered as the input disturbance with its intensity scaled to 223gal and 395 gal, respectively.



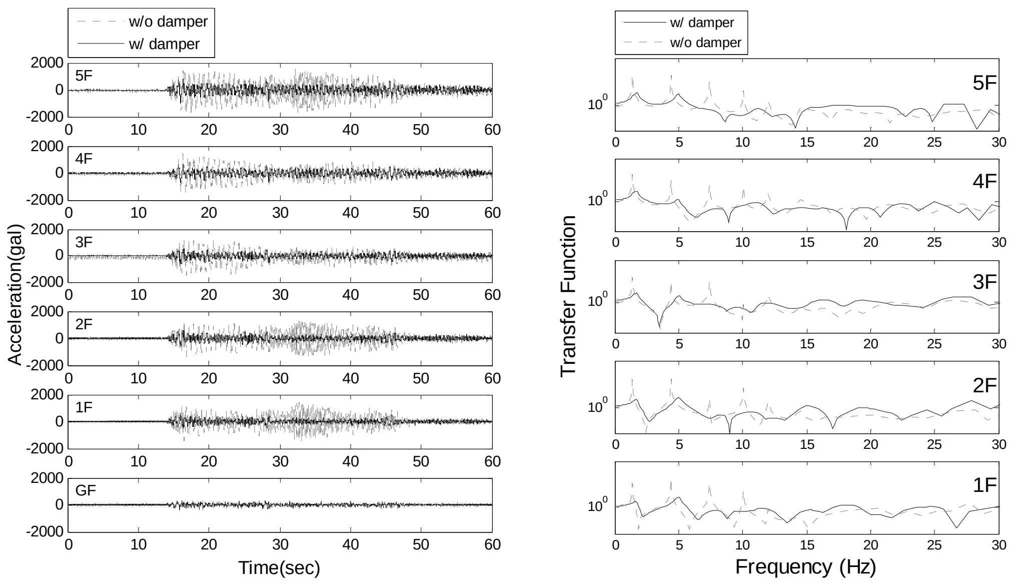
(a) Portal frame. (b) Arched-shape.

Figure 3. Hysteresis of the in-plane flexural dampers from component tests.

The comparisons of the recorded seismic floor accelerations and the frequency responses identified using the ARX model are illustrated in Figure 7 for the case with PGA=395 gal. With the proposed dampers implemented, the response amplitudes of the entire time histories of all floors, without exception, are significantly suppressed. Effectiveness of the structural control with dampers is also revealed from the frequency response functions where the peaks of all five modes are drastically reduced. Comparisons of the peak floor accelerations are summarized in Table 1 for both earthquake intensities. Results indicate that the peak floor accelerations of all floors are significantly reduced. Effectiveness of the seismic performance increases with the earthquake intensity as the dampers are involving more inelastic deformation and therefore dissipating more energy. This is typical for metallic yielding dampers which exhibit nonlinear characteristics in mechanical behavior. The effectiveness is also revealed from the drastic increase of the equivalent damping ratios of all structural modes identified from the experimental data using the ARX model, as summarized in Table 2. The dampers add not only damping but stiffness to the structure, as reflected from the shift of the natural frequencies.

4 CONCLUSIONS

An in-plane flexural metallic damper that utilizes the material more efficiently has been proposed. Both component test and seismic performance test of the damper have been conducted. The component test indicates consistent energy-dissipative characteristics of the damper in an arched shape. Excellent seismic performance of the arched damper has been demonstrated. Experimental results indicate that, with the dampers implemented, the acceleration responses of all floors are significantly reduced and damping ratios of all modes are considerably enhanced. Control effect increases with the earthquake intensity as more inelastic deformation involved in the earthquake scenario.



(a) Time histories. (b) Frequency Responses.

Figure 7. Comparison of floor accelerations under El Centro earthquake (PGA=395gal).

Table 1. Comparison of peak floor accelerations under El Centro earthquake.

	PGA=236gal			PGA=395gal		
Floor	w/o damper (gal)	w/ damper (gal)	Reduction (%)	w/o damper (gal)	w/ damper (gal)	Reduction (%)
5F	1069	572	46	1803	989	45
4F	869	466	46	1466	764	48
3F	916	421	54	1544	616	60
2F	803	368	54	1354	598	56
1F	849	337	60	1432	465	68

Table 2. Modal parameters identified from test data.

Mode	w/o damper		w/ damper (PGA=236 gal)		w/ damper (PGA=395 gal)	
	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
1	1.41	0.70	1.94	10.51	1.69	11.86
2	4.42	0.22	5.28	3.69	4.98	4.17
3	7.41	0.20	9.12	5.33	8.84	5.11
4	10.06	0.17	12.11	4.21	11.31	7.03
5	11.98	0.48	14.27	7.78	14.96	5.44

Acknowledgments

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References

Boresi, A. P., Schmidt, R. J., Sidebottom and O. M., *Advanced Mechanics of Materials*, 5th Ed., Wiley, New York, 1993.

Chan, W.K. and Albermani, F., Experimental Study of Steel Slit Damper for Passive Energy Dissipation, *Engineering Structures*, 30, 1058-1066, 2008.

Guan, Z., Li, J. and Xu, Y., Performance Test of Energy Dissipation Bearing and Its Application in Seismic Control of a Long-Span Bridge, *Journal of Bridge Engineering*, *ASCE*, 15, 622-630, 2010.

Park J.H. and Lee K. H., *Cyclic Loading Tests of Steel Dampers Utilizing Flexure-Analogy Deformation*, 15TH World Conference on Earthquake Engineering, Lisbon, Portugal, September 24~28, 2012.

Timoshenko, S.P. and Goodier, J. N., *Theory of Elasticity*, 3rd Ed., McGraw-Hill, New York, 1970.

Tsai K.C., Chen H.W., Hong C.P. and Su Y.F., Design of Steel Triangular Plate Energy Absorbers for Seismic-Resistant Construction, *Earthquake Spectra*, 9(3), 505-528, 1993.

Wang W.Y., *Mechanics of Material and Testing of in-Plane Arched Damper*, Master dissertation, Department of Civil Engineering, College of Engineering, National Chiao-Tung University, Taiwan, 2014. (in Chinese)

Wang, Y.P. and Chang Chien C. S., A Study on Using Pre-Bent Steel Strips as Seismic Energy-Dissipative Devices, *Earthquake Engineering & Structural Dynamics*, 38, 1009-1026, 2009.

Whittaker, A.S., Bertero, V.V., Thompson, C.L. and Alonso, L.J., Seismic Testing of Steel Plate Energy Dissipation Devices, *Earthquake Spectra*, 7(4), 563-604, April, 1991.