An Experimental Verification of Seismic Structural Control Using in-Plane Metallic Dampers

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***Abstract*—As an effort to minimize material utilization of metallic yielding dampers, steel dampers designed to deform inelastically in an in-plane flexural mode have attracted serious attentions recently. This paper presents a new type of in-plane flexural damper referred to as the in-plane arch-shaped damper modified from its portal frame-shaped counterpart to minimize the effects of stress concentration and warping, and to avoid premature failure as a result. Seismic performance assessment of the proposed damper was carried out via shaking table tests of a five-story model frame under the El Centro earthquake with various intensities. Significant reductions of the structural acceleration and displacement responses have been achieved with the proposed device implemented, and the equivalent damping ratios of all structural modes identified from the experimental data are considerably enhanced. Encouraging test results suggest the effectiveness and feasibility of using the proposed in-plane arch-shaped energy-dissipative device for earthquake protection of building structures. Moreover, a series of nonlinear time history analysis of the five-story model frame corresponding to the tests was further conducted. The inelastic behavior of the proposed dampers was simulated by the Bouc-Wen's model and the predicted acceleration and displacement responses were in turn compared with the experimental results. The simulated structural responses with properly selected parameters of the Bouc-Wen's model agree well with the experimental results, indicating that the proposed analytical model for nonlinear dynamic analysis of inelastic systems is adequate.**

***Index Terms*—seismic, in-plane metallic damper, shaking table tests, Bouc-Wen's model, nonlinear dynamic analysis**

I. INTRODUCTION

Supplemental energy-dissipative dampers [1-3] have nowadays been widely adopted for earthquake-protection of both new and existing building structures. Metallic yielding dampers such as the added damping and stiffness (ADAS) [4-8], triangular-plate added damping and stiffness (TADAS) [9], the buckling restrained braces (BRB) [10], [11] or the pre-bent strips [12] that utilize the strength and ductility of common structural steel plates are alternatives considered to be cost-effective. The aforementioned metallic dampers are commonly designed to deform in an out-of-plane flexural mode (e.g. ADAS and TADAS) by resisting the load against the weak axis of the steel plates. In order to dissipate a substantial amount of energy, the out-of-plane flexural dampers with relatively low stiffness and strength in their weak direction require more steel plates in parallel to achieve the desired stiffness and strength for practical use.

As an effort to minimize material utilization, metallic yielding dampers designed to deform inelastically in an in-plane flexural mode have attracted serious attentions recently, such as the in-plane "dual function" metallic damper (DFMD) with various geometric shapes (e.g. X-shaped, double X-shaped, single-rounded-hole, double-rounded-hole and strip) [13], the in-plane portal frame-shaped damper with slots in the horizontal part [14], the steel slit dampers (SSD) [15], [16] and the comb-teeth damper (CTD) [17] consisting of a series of parallel parabolic shape of the steel links (or teeth) to dissipate energy.

In addition to building applications, the energy dissipation bearing (EDB) constructed by connecting the friction pendulum system (FPS) with an in-plane damper in an E-shaped configuration developed by [18] is considered for seismic isolation of the Nanjing Jia River Bridge in Nanjing, China. The E-shaped damper is forced to deform as the bearing slides during earthquakes and dissipates seismic energy by deforming inelastically.

In this paper, a new type of metallic yielding damper referred to as the in-plane arch-shaped damper (Fig. 1) [19-23] is proposed. Modified from its frame-shaped counterpart by replacing the straight beam with a circular arch, the proposed damper minimizes the effects of stress concentration and warping, and therefore avoids premature failure of the damper. Seismic performance

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assessment of the proposed damper has been carried out via shaking table tests of a five-story model frame. Moreover, a nonlinear time history analysis of the five-story steel model frame implemented with the in-plane arch-shaped dampers simulated by the Bouc-Wen's model [24] has been further conducted and the predicted structural responses were in turn compared with the experimental results.

Figure 1. In-plane arch-shaped damper [23].

II. Nonlinear Time History Analysis

In order to validate the proposed numerical model of the in-plane arch-shaped damper for nonlinear dynamic analysis, a nonlinear time history analysis of the 5-story steel model frame implemented with the dampers (on the lowest three stories, Fig. 2) under the earthquake excitation was conducted to predict the structural responses. The bi-linear hysteretic restoring force ($R(t)$) or the hysteresis loop of the in-plane arch-shaped damper is simulated by the Bouc-Wen's model [24] as:

$$R(t) = \alpha K_1 u(t) + (1-\alpha) K_1 z(t) \tag{1}$$

in which K_1 and α are the initial stiffness and the post-yielding stiffness ratio of the scaled-down in-plane arch-shaped damper, respectively, $u(t)$ is the displacement of the damper (or the relative displacement of the bracings connecting the damper) and the hysteretic displacement $z(t)$ is defined as:

$$\dot{z}(t) = \dot{u}(t)\left\{A - \left[\beta \mathrm{sign}(z(t)\dot{u}(t)) + \gamma\right] | z(t) |^n \right\} \tag{2}$$

where sign denotes the signum function, $A > 0$, $\beta > 0$, γ and n are dimensionless quantities controlling the behavior (or shape) of the model.

Moreover, the equation of motion of the 5-story steel model frame implemented with the in-plane arch-shaped dampers under the earthquake excitation can be represented as:

$$\mathbf{M}\ddot{\mathbf{x}}(t) + \mathbf{C}\dot{\mathbf{x}}(t) + \mathbf{K}\mathbf{x}(t) + \mathbf{R}(t) = -\mathbf{M}\mathbf{1}\ddot{u}_g(t) \tag{3}$$

in which $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are, respectively, the mass, damping and stiffness matrices of the 5-story steel model frame, $\mathbf{x}$ is the displacement vector of the 5-story steel model frame (relative to the ground), $\mathbf{1}$ is the column vector with each element of 1, $\ddot{u}_g(t)$ is the ground acceleration time history, and $\mathbf{R}(t)$ is the restoring force vector of the dampers applying on the structure in the horizontal direction as:

$$\mathbf{R}(t) = \begin{bmatrix} 0 \\ 0 \\ -R_3(t)\cos\theta_3 \\ -R_2(t)\cos\theta_2 + R_3(t)\cos\theta_3 \\ -R_1(t)\cos\theta_1 + R_2(t)\cos\theta_2 \end{bmatrix} \tag{4}$$

where the restoring force of each damper along the direction of the bracings can be represented by using the corresponding inter-story drift of the 5-story steel model frame as:

$$R_1(t) = 2\alpha K_1 x_1(t)\cos\theta_1 + 2(1-\alpha)K_1 z_1(t) \tag{5a}$$

$$R_2(t) = 2\alpha K_1[x_2(t) - x_1(t)]\cos\theta_2 + 2(1-\alpha)K_1 z_2(t) \tag{5b}$$

$$R_3(t) = 2\alpha K_1[x_3(t) - x_2(t)]\cos\theta_3 + 2(1-\alpha)K_1 z_3(t) \tag{5c}$$

in which θ_i $(i = 1,2,3)$ is the angle between the bracing and the horizontal direction on the i-th floor of the model frame.

In this paper, the theoretical parameters of the scaled-down in-plane arch-shaped damper, $K_1 = 0.4549$ kN/mm (the initial stiffness), $\alpha = 0.075$ (the post-yielding stiffness ratio) [25], together with $A = 1.0$, $\beta = 0.5$, $\gamma = 0.5$ and $n = 2.0$ governing the Bouc-wen's model will be adopted to simulate the bi-linear hysteretic behavior of the damper. Moreover, the hysteretic displacement $z(t)$ governed by the nonlinear differential equation (2) and the dynamic structural responses of the 5-story steel model frame under the El Centro earthquake represented by (3) can be solved by integrating the fourth-order Runge-Kutta method [26] and the state space procedure [27-29].

III. Seismic Performance Tests

A. Experimental Setup

To assess the effectiveness of using the proposed in-plane arch-shaped damper for seismic vibration control, a series of seismic performance tests has been conducted using a uni-axial shaking table of 10-ton payload. A 5-story steel model frame (total height of 6.7 m) implemented with in-plane arch-shaped dampers (Fig. 3) on the lowest three stories via diagonal bracings on both sides of the frame parallel to the excitation direction of the shaking table has been tested under the 1940 El Centro earthquake with its intensity scaled to 236 gal and 395 gal, respectively. However, due to the length limitation of the paper, only the results corresponding to PGA=395 gal are presented in this paper.

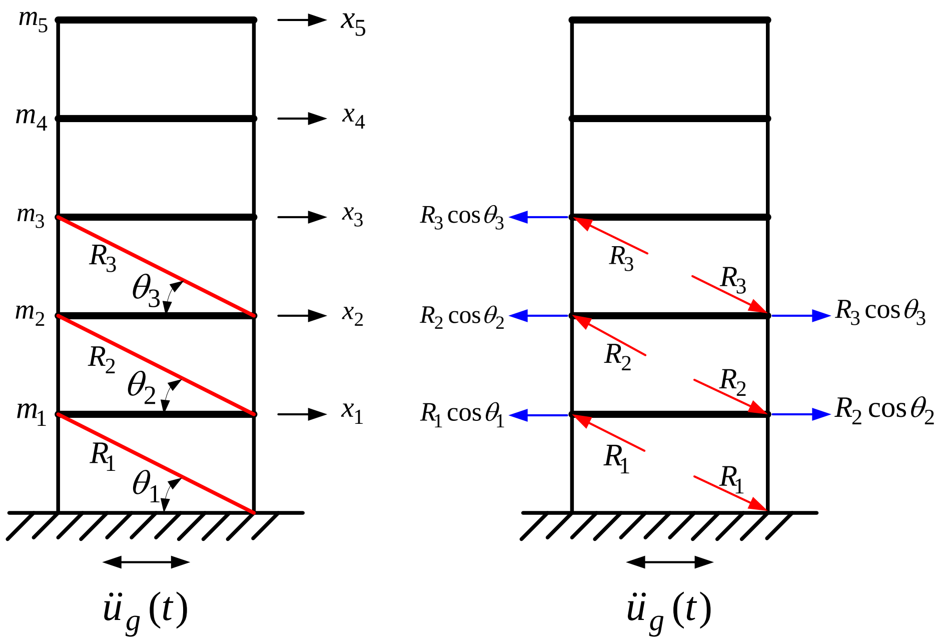

Figure 2. The restoring forces of the in-plane arch-shaped dampers considered in the nonlinear time history analysis of the 5-story steel model frame.

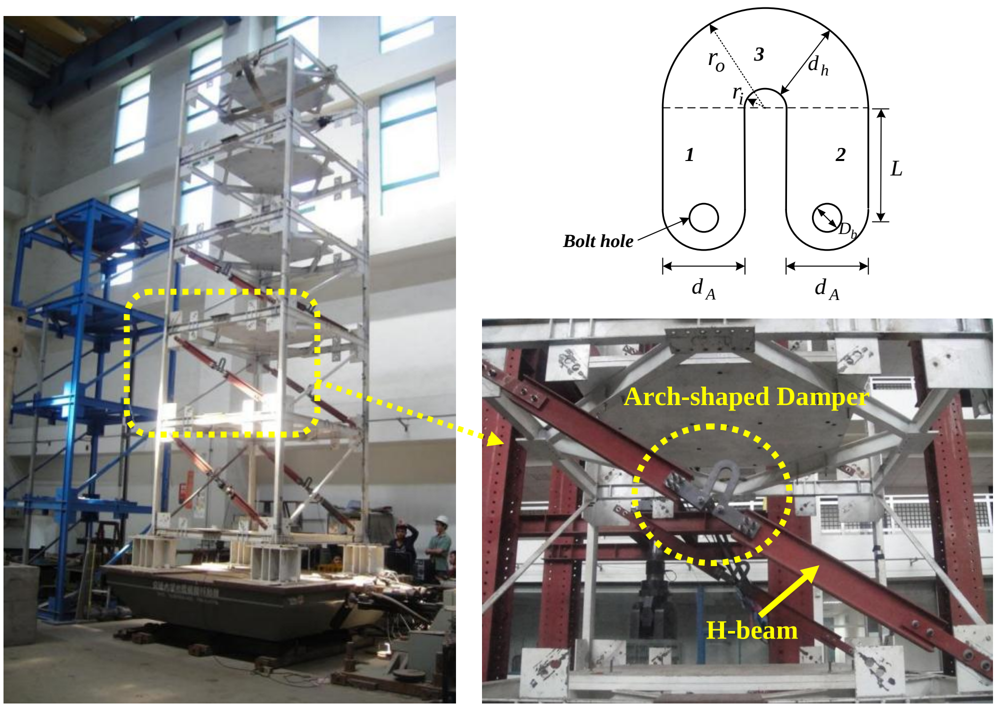

Figure 3. Experimental setup of a 5-story steel model frame implemented with in-plane arch-shaped dampers.

Dimensions of the scaled-down in-plane arch-shaped dampers implemented are: t =5 mm, L =115 mm, $d_h = d_A$ =25 mm, r_i =20 mm, r_o =45 mm and D_b =11 mm (Fig. 3). The initial stiffness of the scaled-down in-plane arch-shaped damper was computed as $K_1 = 0.4549$ kN/mm [25]. Accelerometers (CROSSBOW ±4 g) were implemented on each floor (including the ground motion on shaking table) to monitor the dynamic responses. A load cell of Jihsense (model number: LM-2T) with a capacity of 2000 kgf was installed in series with the in-plane arch-shaped dampers in the first story to measure the force dynamically. Moreover, a laser displacement sensor of Wenglor with a dynamic range of ±15 cm was installed on the diagonal bracing (along the longitudinal direction) in the first story to monitor the damper displacement defined as the relative displacement along the steel bracings in the direction orthogonal to the two straight arms of the damper. The model structure without damping devices was tested with a moderate earthquake intensity to prevent it from potential damage. The recorded seismic responses were then scaled to the level of the earthquake intensity under which the model with damping devices was actually tested for purpose of comparison.

B. Test Results

Fig. 4 shows the seismic floor accelerations of the 5-story model frame under the El Centro earthquake with PGA=395 gal. With the damping devices implemented, the acceleration responses of the model structure have shown to reduce significantly for all floors. The peak floor acceleration reduction ranges from 45% to 68%, and the RMS acceleration reduction by over 59% throughout the floors as summarized in Table Ⅰ and Table Ⅱ, respectively.

TABLE I. COMPARISON OF PEAK FLOOR ACCELERATION UNDER EL CENTRO EARTHQUAKE (PGA=395 GAL)

Floor	Peak responses (gal)		
	w/o damper	w/ damper	Reduction (%)
5F	1803	989	45
4F	1466	764	48
3F	1544	616	60
2F	1354	598	56
1F	1432	465	68

TABLE II. COMPARISON OF RMS FLOOR ACCELERATION UNDER EL CENTRO EARTHQUAKE (PGA=395 GAL)

Floor	RMS responses (gal)		
	w/o damper	w/ damper	Reduction (%)
5F	533	195	63
4F	381	156	59
3F	333	130	61
2F	409	123	70
1F	383	104	73

Fig. 5 shows the seismic floor displacements of the 5-story model frame under the El Centro earthquake with PGA=395 gal. With the damping devices implemented, the displacement responses of the model structure have shown to reduce significantly for all floors. The peak floor displacement reduction ranges from 44% to 54%, and the RMS displacement reduction by over 66% throughout the floors as summarized in Table III and Table Ⅳ, respectively. Moreover, the overall peak inter-story drift ratio (IDR) of 5.38% (on the first floor) of the 5-story steel model frame without control was reduced to 2.83% (on the second floor).

Comparisons of the experimental and numerical acceleration and displacement time histories are provided in Figs. 6 and 7, respectively. The simulated acceleration and displacement responses with $K_1 = 0.4549$kN/mm and $\alpha = 0.075$ for the scaled-down damper and $A = 1.0$, $\beta = 0.5$, $\gamma = 0.5$ and $n = 2.0$ for the Bouc-wen's model agree well with the experimental results, indicating that the proposed bi-linear hysteretical model is proved to be adequate for the nonlinear numerical analysis. Moreover, the simulated hysteresis loops (or the energy-dissipation capability) of the damper on the first floor (Fig. 8) were found overestimated and lead to discrepancy at some peak values of the displacement responses as illustrated in Fig. 7.

TABLE III. COMPARISON OF PEAK FLOOR DISPLACEMENT UNDER EL CENTRO EARTHQUAKE (PGA=395 GAL)

Floor	Peak responses (cm)		
	w/o damper	w/ damper	Reduction (%)
5F	15.47	8.64	44
4F	14.39	7.70	46
3F	11.87	6.08	49
2F	10.12	5.20	49
1F	8.08	3.75	54

TABLE IV. COMPARISON OF RMS FLOOR DISPLACEMENT UNDER EL CENTRO EARTHQUAKE (PGA=395 GAL)

Floor	RMS responses (cm)		
	w/o damper	w/ damper	Reduction (%)
5F	4.74	1.62	66
4F	4.31	1.44	67
3F	3.49	1.11	68
2F	2.89	0.92	68
1F	2.22	0.62	72

Moreover, the equivalent damping ratios of all structural vibration modes identified from the recorded acceleration time history data under the El Centro earthquake by using the ARX method [30] with model order of 100 considered at PGA=395 gal have shown to increase significantly, as summarized in Table V. With the in-plane arch-shaped dampers implemented, the equivalent damping ratio of the fundamental mode has enhanced from 0.70% to 11.86% for PGA=395 gal. It is found, on the other hand, that the dampers add not only damping but also stiffness to the structure, as reflected from the shift of the identified equivalent natural frequency of the fundamental mode from 1.41 Hz to 1.69 Hz for PGA=395 gal. The structure is comparatively less stiff for stronger earthquake as more yielding of the dampers involved during the course of excitation.

TABLE V. MODAL PARAMETERS IDENTIFIED FROM EXPERIMENTAL ACCELERATION TIME HISTORY DATA UNDER EL CENTRO EARTHQUAKE (PGA=395 GAL)

Mode	w/o damper		w/ damper	
	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
1	1.41	0.70	1.69	11.86
2	4.42	0.22	4.98	4.17
3	7.41	0.20	8.84	5.11
4	10.06	0.17	11.31	7.03
5	11.98	0.48	14.96	5.44

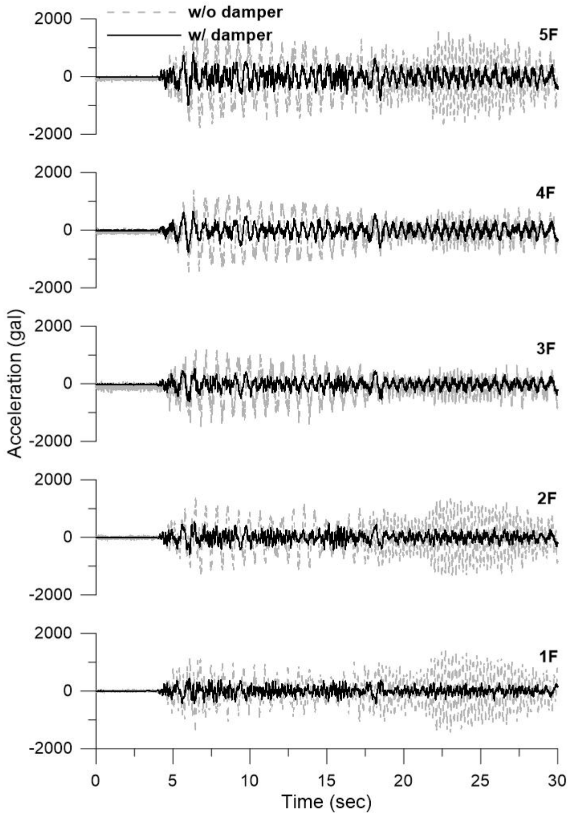

Figure 4. Comparison of the seismic acceleration responses with and without the in-plane arch-shaped dampers (PGA=395 gal).

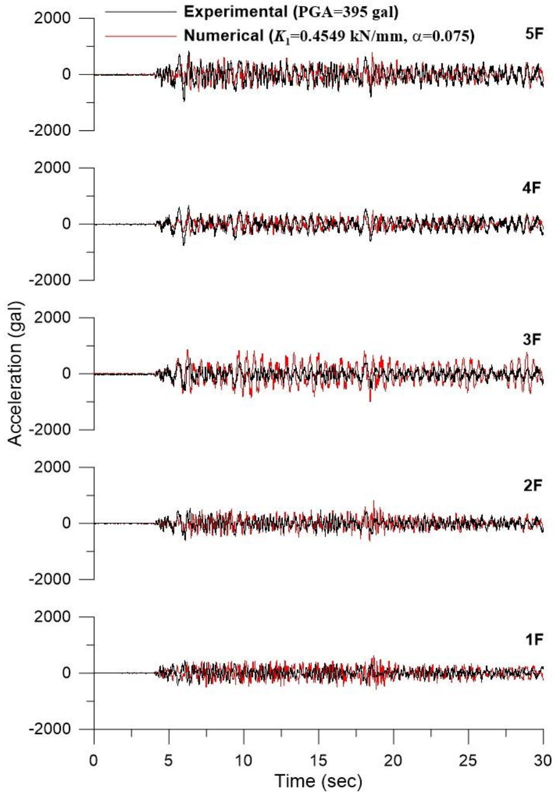

Figure 6. Comparison of the experimental and numerical seismic acceleration responses obtained from nonlinear time history analysis (PGA=395 gal).

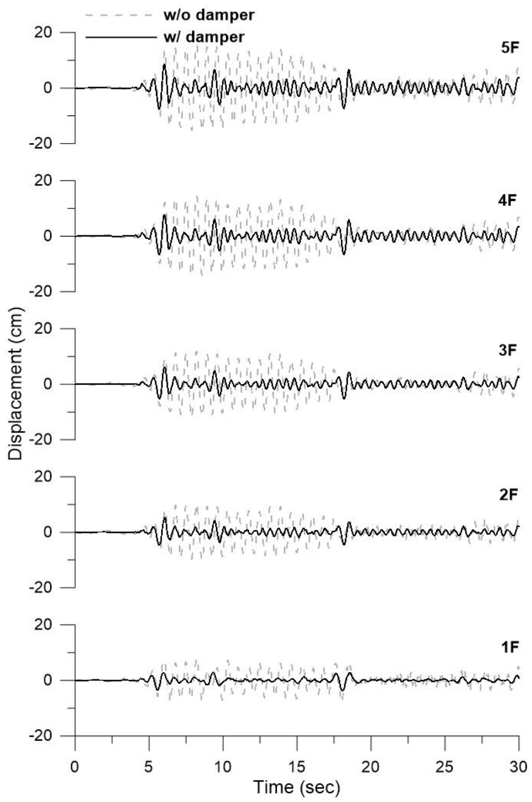

Figure 5. Comparison of the seismic displaccement responses with and without the in-plane arch-shaped dampers (PGA=395 gal).

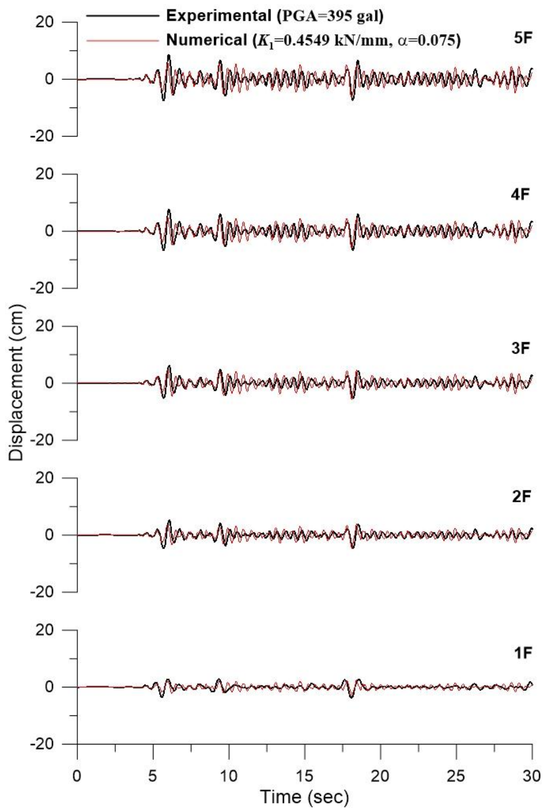

Figure 7. Comparison of the experimental and numerical seismic displacement responses obtained from nonlinear time history analysis (PGA=395 gal).

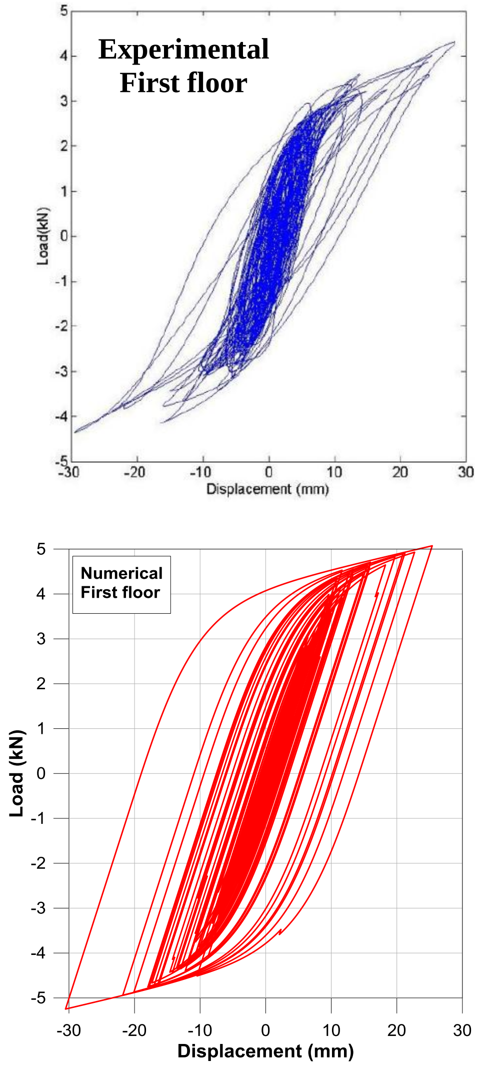

Figure 8. Simulated hysteresis loops of the in-plane arch-shaped dampers implemented on the first story of the 5-story steel model frame (El Centro earthquake, PGA=395 gal).

IV. Conclusions

In this paper, the in-plane arch-shaped damper that utilizes the material more efficiently and alleviates the effect of stress concentration to prevent the premature failure of the damper has been proposed. Seismic performance tests of the in-plane arch-shaped damper has been conducted via shaking table tests of a five-story steel model frame under the El Centro earthquake at different level of seismic intensities. Significant reductions of the structural acceleration and displacement responses have been achieved with the proposed device implemented and the equivalent damping ratios of all structural modes identified from the experimental data are considerably enhanced. Moreover, the predicted structural responses with properly selected parameters of the Bouc-Wen's model agree well with the experimental results, indicating that the proposed analytical model for nonlinear dynamic analysis of inelastic systems is adequate. Encouraging test results suggest the effectiveness and feasibility of using the proposed in-plane arch-shaped energy-dissipative device for earthquake protection of building structures.

Acknowledgment

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