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Full Length Research Paper

A new finite element investigation on pre-bent steel strips as damper for vibration control

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In this study, a new type of seismic energy-dissipative device in the form of braces based on pre-bent strips has been utilized. In this approach, moment-resistance frame systems have been used for 3, 5, 7, 9, 11 and 12 stories and various models. The height of stories and all span lengths are 3 m. In order to compare the response of models, braced (with damper) and unbraced (without damper) have been modeled. Pre-bent steel strips have been used in braced frames. A bilinear strain-stress model of mild steel has been used in this simulation. The responses of structures with dampers and without dampers under dynamic loading have been compared. The results show that seismic responses, such as base shear, story acceleration and story velocity of 3, 5, 7, 9, 11 and 12 story frames with dampers have been improved (reduced) and these reductions have been decreased from 3 story frames to 12 story frames. This damper reduces the displacement of models on upper stories. A series of time history inelastic dynamic analyses have been conducted and the results show the feasibility and effectiveness of using the utilized devices as seismic dampers to reduce structural responses, such as base shear, acceleration, velocity and displacement of stories. This new kind of dissipative device controls seismic damage and reduces story responses under cyclic loading.

Key words: Pre-bent strips, response of structure, damper, energy dissipation.

INTRODUCTION

In this study, a new type of seismic damper is utilized and simulated, which assesses the performance of pre-bent steel strips as seismic energy dissipative devices. Nowadays, one of the important criteria for designing structures is seismic safety. Vibration control and energy dissipation, which provide the seismic safety with suitable equipment, are the essential bases of this paper for utilizing seismic dampers. Energy dissipaters are a convenient option for the design of earthquake resistant structures since these devices absorb the input energy to reduce the damage of vibration and seismic responses. Using vibration control technology leads to the design of new types of earthquake resistant structures. The reduction and improvement of structural responses, such as base shear, acceleration, displacement and velocity, are the ultimate aim of this paper, which is possible through the utilization of dampers in structures without retrofitting each of the structural members. A new type of damper has been utilized and the idea has been expanded in this study with finite element method (FEM) using pre-bent steel strips. According to the importance of structural safety, pre-bent steel strips have been selected for this study, as they are efficient and economical for civil structures.

Investigation of vibration control via isolation with pre-bent struts and strips have been done (Plaut et al., 2008; Jeffers et al., 2008; Plaut et al., 2005; Narmashiri et al., 2010; Ravari et al., 2011), all of whom have studied pre-bent struts as a column for isolation. Virgin and Davis

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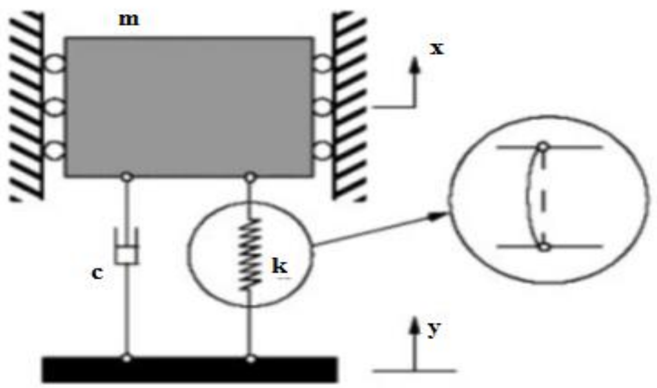

Figure 1. Parallel pre-bent struts as column.

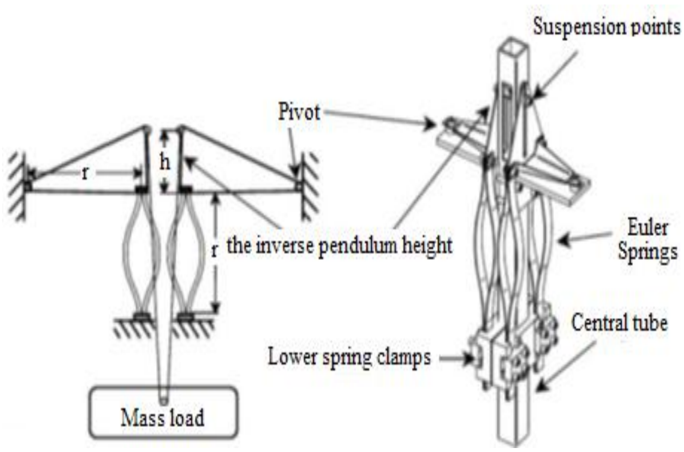

Figure 2. 2D frame with vertical Isolation system.

(2003) developed a vibration control system with parallel pre-bent struts as a simply supported column, as shown in Figure 1.

Chin et al. (2004) simulated pre-bent strips as a vertical spring, which controls excitation responses and reduces the effect of vibration on a 2D frame in the vertical stage, as shown in Figure 2. Plaut et al. (2005) considered vertical struts as pre-bent strips for columns, which support a 2D solid diaphragm as a uniform mass; the columns in that study had clamped supports. Plaut et al. (2008) investigated another characteristic of pre-bent strips as a column in 2D systems; furthermore, Jeffers et al. (2008) completed their study concerning isolation via pre-bent struts by investigating pre-bent strips as a column in a 3D system containing a plate that was supported by 4 pre-bent struts as a column. These studies have proved the efficiency of pre-bent strips as columns in excitation, which reduce the vibration to improve the structural responses of the frame. The last study about pre-bent strips was completed by (Wang and Chien, 2009). The capability of pre-bent strips to

Figure 3. 5-story frame on shaking table.

dissipate energy under cyclic loading was tested and characteristics, such as length of arch and slope, were studied. Furthermore, pre-bent steel strips (Figure 4) have been set up with abrace in a 5-story frame, as shown in Figure 3, which was set up on a shaking table to simulate Kobe and El-Centro acceleration. The seismic performance tests in this exploration proved the feasibility of pre-bent steel strips as seismic energy dissipative devices. The idea of this paper was developed, according to the series of investigations mentioned earlier on pre-bent strips for vibration control.

The main thought of this paper is to develop the idea of vibration control via pre-bent steel strips by numerical simulation. This study, which contains some phases to increase the accuracy of exploration, is a series of simulations and numerical tests on various structural models by ABAQUS. The models have been loaded under cyclic loading-Northridge, Palm Springs.

MATERIALS AND METHODS

The damper was made of metallic strips, which have a primary arc. The arc and pre-bent steel strips have been designed using the same procedure, which started with the approximation and formulization of the primary shape of the pre-bent strips. The pre-bent strips, which were clamped at both ends, can be approximated in terms of the chord-tangent angle function, θ(s) as:

$$\theta(s) = q\,F(s) \tag{1}$$

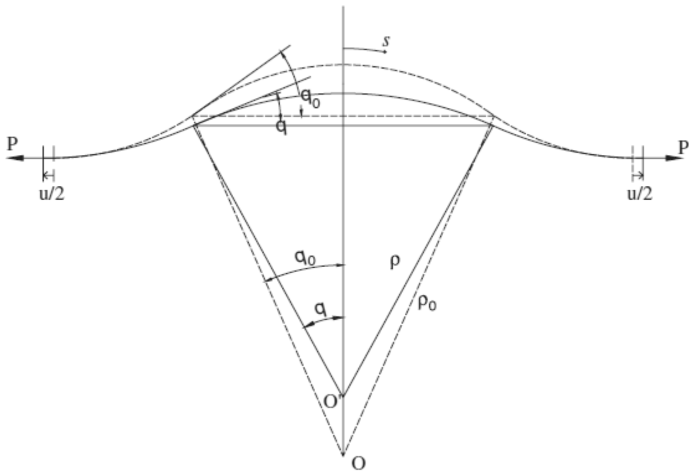

Figure 4. Pre-bent strip in action.

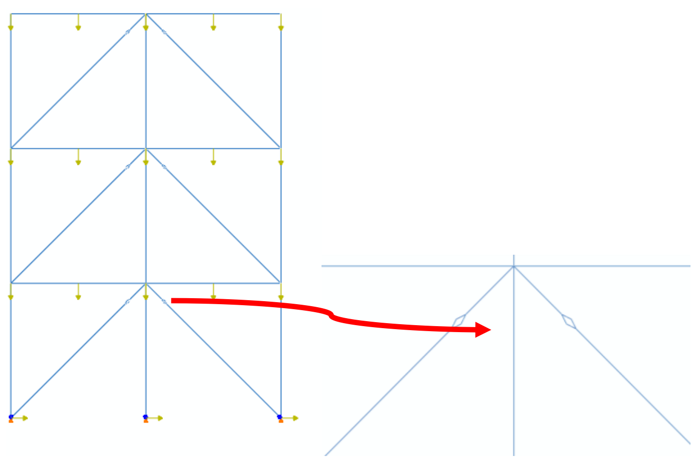

Figure 5. Model with damper under loads.

$$F(s) = sin(\frac{2\pi s}{L}) \qquad \frac{-L}{2} \leq s \leq \frac{L}{2} \qquad (2)$$

In which L is the arc length of the pre-bent strip and *q* is the slope of the tangent at the inflection point at s = L/4

According to Equation (3) (Wang and Chien, 2009):

$$P=P_{cr}\left(1-q_0(q_0{}^2-\frac{2u}{L})^{\frac{1}{2}}\right)\left(\frac{1}{4}(1+\beta)+\frac{1}{\pi^2}(1-\beta)\right)\left(-1-\frac{u}{4L}+\frac{q^2}{8}\right)^{-1} \qquad (3)$$

In which $\beta = \frac{b_0}{b_n}$ is the ratio of the original strip width to neck width; Plaut et al. (2008) concluded that the optimum system for β of pre-bent strip is 1; therefore, in this investigation β is 1.

The models were implemented with pre-bent steel strips and were tested with benchmark earthquakes, namely, the Northridge (PGA = 1 g), Palm Springs (PGA = 1 g) and Friuli (PGA = 1 g) specified according to the models design. Figure 5 shows a sample of the simulated structure, which was loaded under specified earthquakes and tested with and without dampers.

Simulation of the structures with pre-bent steel strips as dampers was conducted with a bilinear stress-strain model of mild steel in which the Young's Modulus was 2×10^5 MPa, and the yielding stress and strain were 2.35 × 102 MPa and 0.001175, respectively, and the post-yielding stiffness ratio was 0.01. In order to simulate the boundary condition of an axially loaded pre-bent strip in a displacement-controlled loading test, the nodal displacements at one end of the strip were fixed in all three directions (x, y, z) and only allowed to slide in the axial direction (x) at the other end.

RESULTS AND DISCUSSION

Responses under each earthquake

To explore the feasibility of pre-bent steel strips as dampers for vibration control, a series of seismic tests under each of the benchmark earthquakes considered earlier was simulated. The outputs of the structural models under cyclic loads prove the efficient damping performance of the pre-bent steel strips. Figure 5 illustrates the samples of the response of certain models that proves the seismic damping performance of pre-bent steel strips. In as much as base shear, acceleration of stories, displacement of stories and velocity are important criteria to design earthquake resistant structures, these seismic structural responses are demonstrated.

Figure 6 shows the damping characteristics of pre-bent steel strips for the Northridge simulated earthquake, which conducts the reduction for base shear, that is, the sum of the nodal forces at each story. As mentioned previously, some reasons for the damping performance of pre-bent steel strips are explainable. These include the nonlinear stiffness of pre-bent strips, which has been proven earlier; another important criterion for seismic response dissipation is the bilinear stress-strain preferences, which are considered for the material of the models. In order to accurately compare many models, different dynamic loadings have been tested. Another sample response for the base shear for Palm Springs (PGA = 1 g) is as shown in Figure 7.

Acceleration responses for each cyclic loading

An important criterion for earthquake resistant structures, which are assessed in this study, is the response of acceleration. In order to test the merit of pre-bent steel strips as dampers, the acceleration responses were detected in numerical models under the bench marked earthquakes previously mentioned. The acceleration responses of the last story in each model are shown subsequently (Figure 9). At first, the summarized outputs for Palm Springs have been demonstrated in Figure 8.

According to the stories acceleration response graphs, since damper width and length in the 12-story structure reaches the upper limit and the strip by primary bending changes its shape, as a strip by a length of 15 cm into a

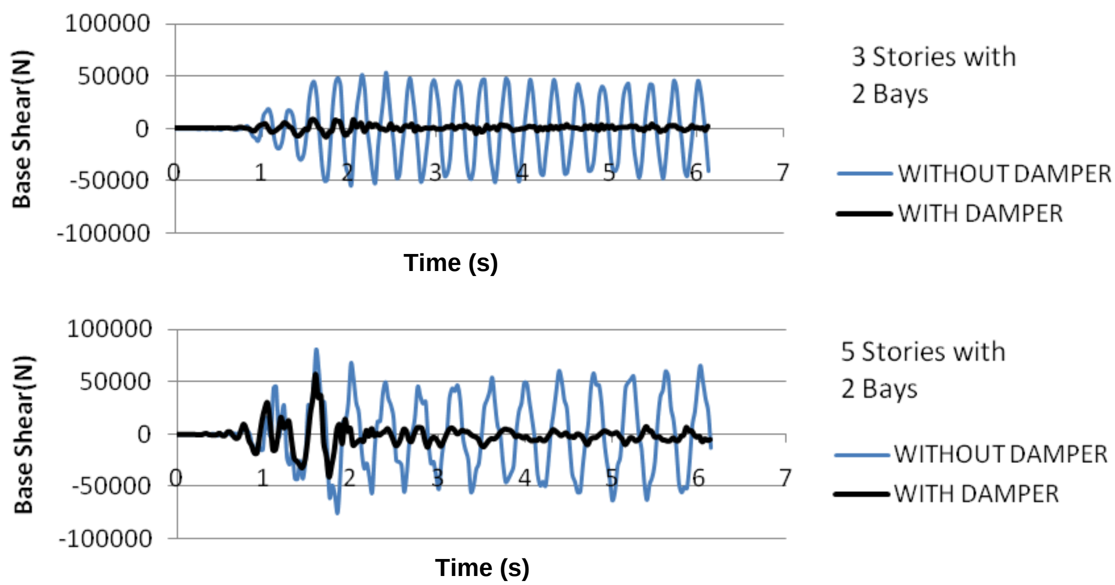

Figure 6. Base shear for structural models, Northridge (PGA = 1 g).

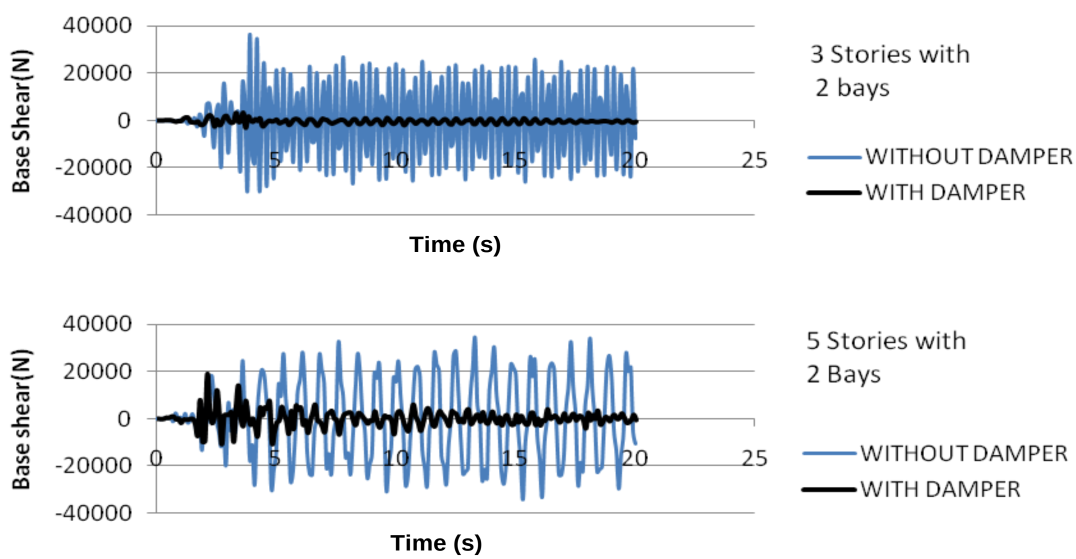

Figure 7. Base shear for structural models, Palm Springs (PGA = 1 g).

plate with a width and length ratio of more than 1; it can be claimed that the optimal damping is expected when the width and length ratio of the damper reduces to a small value and reaches 1 in the optimal state, and dimensional nonlinear elastic behavior is justifiable.

Displacement

The displacement of the stories during shaking and control of these displacements during modeling of damper are analyzed, and the samples of displacement behavior are explained during acceleration (Figure 10).

Velocity

The stories velocity responses during shaking and control of displacement have been analyzed using damper modeling and examples of structural velocity response during the application of the acceleration of the system in Figure 11 are explained.

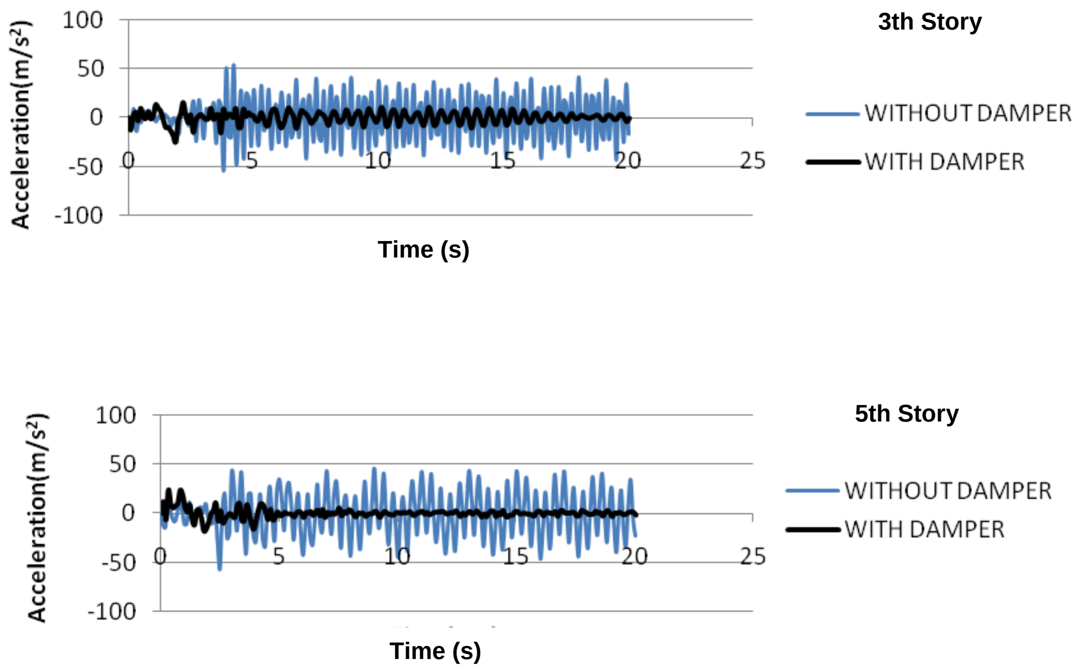

Figure 8. Acceleration responses for the last story of the structural models, Palm Springs (PGA = 1 g).

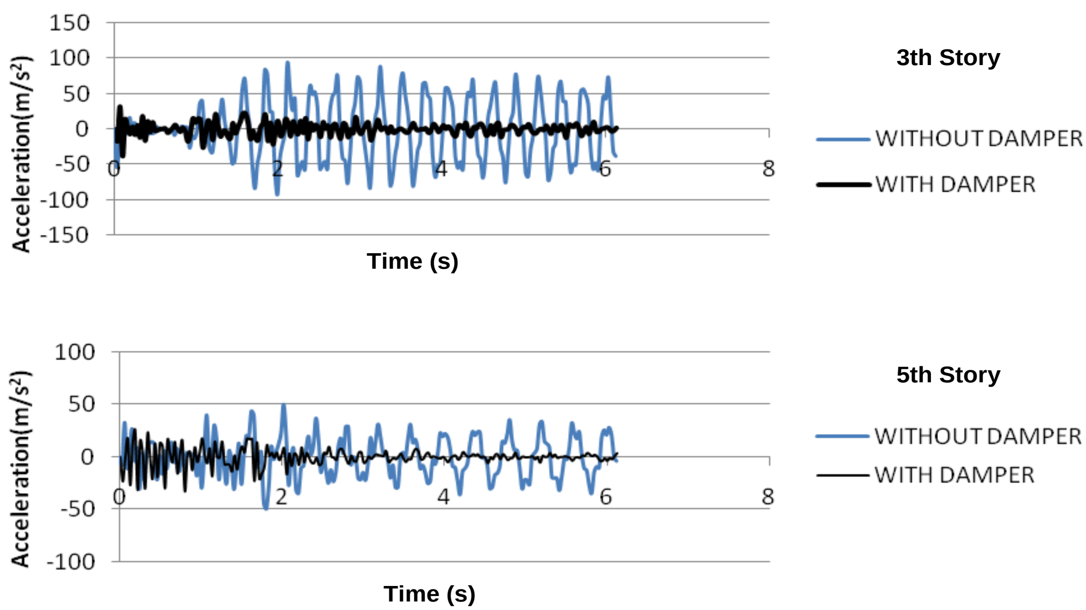

Figure 9. Acceleration responses for the last story of the structural models, Northridge (PGA = 1 g).

The reason for damping performance

According to the responses of the structural models, they have obviously been affected by the damping behavior of the pre-bent steel strips. For explaining the damping performance of pre-bent steel strips, the inelastic behavior of the nonlinear spring (pre-bent steel strip according to Equation 3) can be concluded according to Figure 12, which shows the performance of pre-bent steel strips, for instance.

Figure 12 shows the damping response of pre-bent steel strips, which has resulted from the inelastic

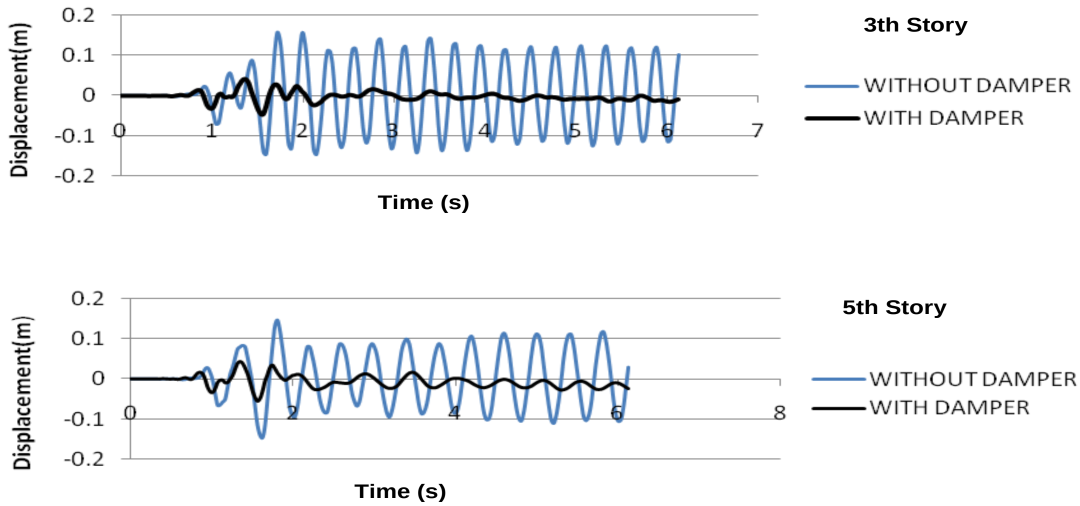

Figure 10. Displacement for the last story of structural models, Northridge (PGA = 1 g).

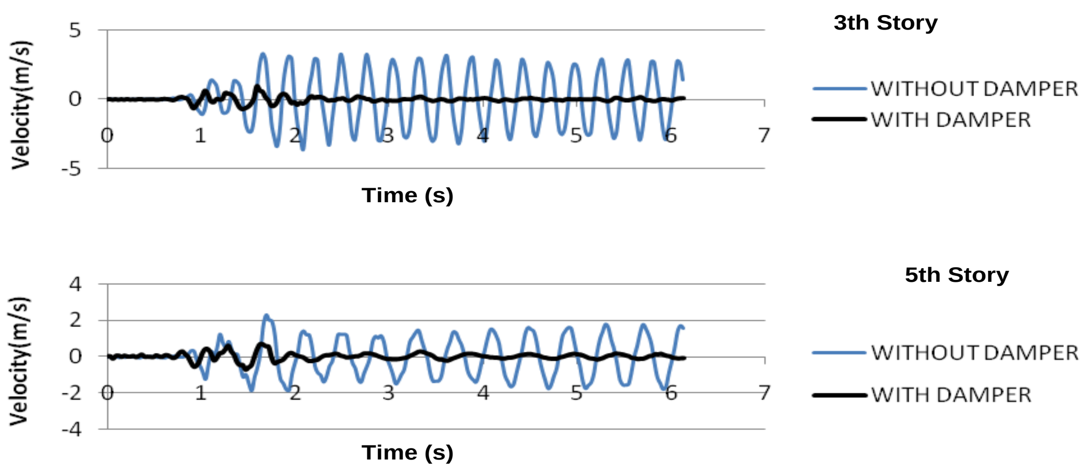

Figure 11. Velocity for the last story of structural models, Northridge (PGA = 1 g).

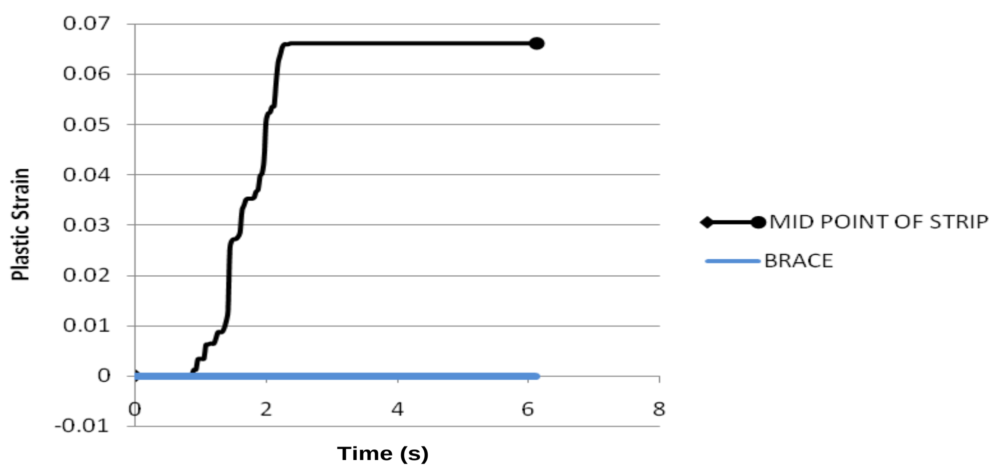

Figure 12. The responses of a damper as opposed to a brace, Northridge (PGA = 1 g).

performance of pre-bent steel strips. Equation 3 demonstrates the axial force, which shows the nonlinear option for the pre-bent strips as a damper (spring), which reacts with this nonlinear stiffness:

$$K = \frac{P(q_0, u, \beta)}{u} \quad (4)$$

Therefore, according the previous explanation, it can be concluded that the combination of nonlinear stiffness and inelastic performance are the reasons for the damping response of pre-bent steel strips.

Conclusion

In this study, a new type of seismic damper has been utilized and simulated on the various structural models, which have been tested under cyclic loads and benchmark earthquakes. The summarized results of this numerical investigation have been demonstrated in this paper. The important responses of structural models, such as base shear, acceleration, displacement and velocity, have been demonstrated. In order to compare the results, the responses have been demonstrated with and without a damper. The seismic tests with FEM in this numerical study confirm the feasibility and effectiveness of pre-bent steel strips as seismic dampers, which reduces the important responses of the structural model effectively.

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