Numerical analysis of U-shaped hysterisis steel damper with energy absorber for seismic areas

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Abstract. This paper investigates one type of metallic dampers used in many large buildings in seismic areas. The previous studies have shown a possibility of the introduced damper to act as a damper as well as energy absorber through yielding on some parts of the damper. However, the occurred yielding caused a plastic deformation after unloading. The study aims to substitute the previous critical area to another part which is considerably uncritical during loading. Therefore, an additional part in the form of a slender column is inserted into the damper. The bottom part of the column is clamped to the base plate of the damper. There is a restoring moment acting on the column which was able to restore a large displacement of the damper to at least a small residual plastic displacement after unloading. A stiffness, strength and energy dissipation of the modified damper is determined by a nonlinear finite element technique which involves both geometrically and materially nonlinearities. The model was subjected by a monotonic increasing load which is applied horizontally through the method of displacement control until one cycle of hysteresis is formed. The final result is in a term of comparison of hysteresis curves between a full model of hysteresis damper with and without a slender column.

1. Introduction

A series of studies which are aimed to improve a design method of space structures, particularly in seismic areas, has been done since the past two decades. This study was started in finding the optimum shape of space structures numerically in resisting the external loads through a method of form finding [1,2]. The result offered the optimum geometry of space structures with the highest strength under loading. Then, a numerical study, called as member proportioning [3,4], was done with the aim to reduce the thickness of uncritical members of the structures. Therefore, the total weight can is reduced. It made the space structures becomes lighter. Combination of both methods was considered able to offer a strong and a light space structure. In term of safety, the studies focussed on searching a mechanism which can act as a damper and also energy absorber when subjected by a heavy load. Satria et al. [5,6] investigated a mechanism of T-joint struts in the design of two-way single-layer lattice dome. The studies concluded that the strut member could act as damage controller due to its ability to absorb the energy of a strong load.

On the other hand, there are many models of energy absorbers for buildings that have been introduced. Some mechanisms like pendulum isolator [7], lead rubber bearing [8], viscous damper [9], and friction damper [10] have been very well studied in recent years. These models were installed into buildings with the aim to reduce the displacement due to the earthquake. However, there is still a few studies
that focused on dissipation of energy through inelastic deformation. Some references have proposed several mechanisms such as bracing [11], viscous-elastic damper [12], concentrically braced frames (13), and hysteresis steel damper [14] for the space structures with the aim to absorb energy from the earthquake.

One mechanism that can be considered able to act as a damper, as well as an energy absorber in the structure, is metallic friction damper. This paper focused on examining characteristics the metallic damper in the form of U-shaped steel damper. The first study had numerically investigated some mechanical characteristics of a single U-plate under cyclic loading [15]. These characteristics were determined statically through the application of finite element technique in modeling and analyzing the damper. The results were given in the form of parameters of stiffness and energy dissipation. Then, these parameters were used in a dynamic analysis to calculate responses of roof structure under earthquake. This roof is connected to the lower structure by the damper. The latest study used a full model of hysteresis damper which is built of a set of U-plate damper pairs. This study showed a possibility of the introduced system could be acted as a damper and also energy absorber through yielding of some parts of the system [16,17]. However, under a heavy load, the yielding firstly occurred in the curved area of U-plate and the residual plastic deformation after unloading is quite large. It means that the U-plate is considerably damaged. Therefore the new one is required. To avoid this condition, the current study aims to substitute the previous critical part to another part which is considerably uncritical during loading. Therefore, in this paper, an additional part, in the form of a slender column, is inserted into the damper. The bottom part of the column is clamped to the base plate of the damper. Consequently, there is a restoring moment acting on the column. This restoring moment is considered able to restore a large displacement after unloading. If the yielding still occurs, the damage can be initially localized in the slender column before reaching the main plate. Rigidity and strength of modified damper are determined by a nonlinear finite element technique which involves both geometrically and materially nonlinearities. The model was subjected by a monotonic increasing load which is horizontally applied through a method of displacement control until one cycle of hysteresis is formed. The stiffness of the damper is directly determined from the curve of load vs. displacement. The final result is in a term of comparison of hysteresis curves between a full model of hysteresis damper with and without a slender column.

2. Material and Method

There are three models of U-shaped hysteresis models are used in this paper, as shown in Figure 1. The first model (later called as Model_01) is only the damper with two pairs of U-shaped plate without slender columns as an energy absorber. The next two models (Model_02 and Model_03) are the dampers using slender column but with different geometries.

2.1. Geometrical Properties of U-Plate

The geometries of U-shaped steel are given in Figure 1, and its sizes are detailly described in Table 1. A hysteresis damper is built of two pairs of U-shaped steels, in x- and y-directions, which connect the upper and the lower holding plate through bolt connections. Then, a slender column is introduced to the damper as a part to absorb seismic energy during an earthquake.

2.2. Material Properties

Material properties of the U-shaped steels are given in Table 2. The material is assumed made of steel with a modulus elasticity of 210000 MPa, a yield strength of 270.1 MPa, a poison ration of 0.3, and a material model of stress-strain is assumed as a bilinear relationship.
Figure 1. Three model of dampers: Model_01 (left), Model_02 (middle) and (c). Model_03 (right)

Figure 2. Geometries of U-Plate

Table 1. Geometries of U-Shaped Plate (dimension in mm)

| Part           | Dimensi          | Model_01 | Model_02 | Model_03 |
|----------------|------------------|----------|----------|----------|
| U-Plate        | Length (L)       | 125      | 125      | 125      |
|                | Width (w)        | 90       | 45       | 90       |
|                | Height (h)       | 150      | 150      | 150      |
|                | Radius (R)       | 75       | 75       | 75       |
|                | Thickness (t)    | 10       | 10       | 10       |
| Holding Plate  | Length (L_h)     | 290      | 290      | 290      |
|                | Width (w_h)      | 290      | 290      | 290      |
|                | Thickness (h)    | 15       | 15       | 15       |
| Column         | Length (L_c)     | -        | 170      | 170      |
|                | Width (w_c)      | -        | 10       | 60       |
|                | Thickness (t_c)  | -        | 10       | 10       |

Table 2. Material Properties

| Property          | Value            |
|-------------------|------------------|
| Modulus of Elasticity | 210000 MPa   |
| Yield Strength    | 270.1 MPa       |
| The ratio of Poisson | 0.3       |
| Model of Stress-Strain | Bilinear |

2.3. Model of Load and Boundary Condition

Loading is assumed to be given in horizontal direction only (x-axis direction), as seen in Figure 4. For this purpose, all nodes on the left side of the upper holding plate are loaded by same forces, P, in the right direction. For modeling of boundary condition, all nodes on the upper side of the upper holding plate are permitted only to displace in the horizontal direction (roller supports), while all nodes on the lower side of the lower holding plate are restrained to displace in all directions (fixed supports).
2.4. Methodology

There are two general analyses used in this paper. In the first analysis, computational programming based on nonlinear finite element analysis was developed to calculate stiffness and energy dissipation under loading. The result of this analysis is given in the form of a curve of load and displacement, as seen in Figure 5. The stiffness of the damper is modeled in a combination of three linear stiffness: $k_1$, $k_{II}$, and $k_{III}$. These parameters are calculated using equation (1), (2) and (3). Moreover, energy dissipation is calculated based on the area of curve load and displacement under one cycle of

\[ k_1 = \frac{P_1}{\delta_1} \]  
\[ k_{II} = \frac{(P_2 - P_1)}{\delta_2 - \delta_1} \]  
\[ k_{III} = \frac{(P_3 - P_2)}{\delta_3 - \delta_2} \]  
\[ c = \frac{E}{\pi\omega\Delta x^2} \]
hysteresis. From this energy dissipation, the damping ratio (c) is calculated from equation (4). Parameters E, \( \omega_0 \), and \( \Delta X \) in this equation refer to energy dissipation, the frequency of load and the maximum amplitude of the hysteresis cycle.

In the second analysis, a building structure is modeled using a simple model of spring-mass, as seen in Figure 6, and the displacement of the upper structure which represent the roof of the building was calculated using an in-house computational program. The dynamic analysis is aimed at two models. The first model is used for the basic model without the introduced damper (see Figure 6a). Mass of the model is a total mass of upper and lower structure (m1 and m2), and this mass is connected to the ground using large stiffness (k1) and small damping ratio (c1). These parameters are given based on the assumption. Therefore, the model is derived as 1 DOF with the differential equation is given in equation (2). The second model is used for the advanced model with the introduced damper (see Figure 6b). The upper structure is connected to the lower structure through application of damper with the stiffness of k2, and damping ratio of c2, while the stiffness (k1) and damping ratio (c1) to the ground are assumed similar with the first model. Both parameters, k1 and c1, are produced from the previous static analysis. The model is derived as 2 DOF with the differential equation of the model given in equation (3).

\[
(m_1 + m_2) \ddot{x}_1 + c_1 \dot{x}_1 + k_1 x_1 = u(t)
\]  

(5)

\[
\begin{bmatrix}
    m_1 & 0 \\
    0 & m_2
\end{bmatrix}
\begin{bmatrix}
    \ddot{x}_1 \\
    \ddot{x}_2
\end{bmatrix}
+
\begin{bmatrix}
    c_1 + c_2 & -c_2 \\
    -c_2 & c_1
\end{bmatrix}
\begin{bmatrix}
    \dot{x}_1 \\
    \dot{x}_2
\end{bmatrix}
+
\begin{bmatrix}
    k_1 + k_2 & -k_2 \\
    -k_2 & k_1
\end{bmatrix}
\begin{bmatrix}
    x_1 \\
    x_2
\end{bmatrix}
=
\begin{bmatrix}
    u(t) \\
    0
\end{bmatrix}
\]  

(6)

The earthquake load \( u(t) \) is given at the ground of the spring-mass model, using the elcentro earthquake, as seen in Figure 6.

![Figure 6. Elcentro Earthquake Load](image)

3. Results and Discussion

3.1. Static Analysis

Static analysis of U-shaped steel dampers is carried out based on the concept of finite element method which involves the nonlinearity of geometry of the material. An in-house computational program had been developed for this purpose. The results are presented in the form of a hysteresis curve, as seen in Figure 8, and detaiily described in Table 3. In general, under cyclic horizontal loading, the resulted stiffness of each damper is given in the form of a nonlinear relationship. Therefore the stiffness is better to be approached by three linear stiffnesses, as presented by parameters \( k_1 \), \( k_{II} \) and \( k_{III} \). For example for Model_01, a model without a column, these linear stiffnesses are \( k_1=8975.96 \) N/mm, \( k_{II}=3492.53 \) N/mm and \( k_{III}=572.22 \) N/mm. Then, due to the application of the slender column (see
Model_02), the stiffnesses increase to be $k_{I}=10582.00$ N/mm, $k_{II}=4199.84$ N/mm and $k_{III}=1274.39$ N/mm. The small increases occur because the used column is very slender in size. Therefore the effect of this column in absorbing the energy due to the given load is not significant enough. However, when the size of cross section of the column is modeled bigger than Model_02, as seen in Model_03, the stiffnesses increase significantly to be $k_{I}=18960.15$ N/mm, $k_{II}=8178.98$ N/mm and $k_{III}=4807.83$ N/mm. Moreover, in term of energy dissipation, Model_03 gives the largest area of load-displacement compared to the other two models. It is given around $E_{3}=5902251\times10^{3}$ N.mm, compared to $E_{2}=2812883\times10^{3}$ N.mm of Model_02 and $E_{1}=2332631\times10^{3}$ N.mm of Model_01. To determine the damping ratio, equation (4) is used with assumptions are $\omega=0.08$ Hz and $\Delta X=20$ mm. The damping ratio of Model_03 is $c_{3}=46992.45$ N.s/mm, $c_{2}=22395.57$ N.s/mm of Model_02 and $c_{1}=18571.91$ N.s/mm of Model_01. It means that Model_03 presents the best damping characteristic than the others. The modes of deformation of the dampers are shown in Figure 7.

![Figure 7. Load-displacement relationship (P-\(\delta\)) of the damper under cyclic load](image)

**Table 3.** Stiffness ($k$), load ($P$), energy dissipation ($E$), and damping ratio ($c$) of the models

| Model | $P_{1}$ N | $P_{2}$ N | $P_{3}$ N | $k_{I}$ N/mm | $k_{II}$ N/mm | $k_{III}$ N/mm | $E$ N.mm$\times10^{3}$ | $c$ N.s/mm |
|-------|----------|----------|----------|-------------|--------------|-------------|----------------|-------------|
| 1     | 27825.49 | 40398.58 | 48009.09 | 8975.96     | 3492.53      | 572.22      | 2332631        | 23203.10    |
| 2     | 31745.99 | 47285.39 | 64234.83 | 10582.00    | 4199.84      | 1274.39     | 2812883        | 27980.30    |
| 3     | 49296.40 | 85283.81 | 147785.55| 18960.15    | 8178.98      | 4807.83     | 5902251        | 58710.80    |

3.2. Dynamic Analysis

The dynamic analysis aims to examine the feasibility of the damper to be applied in building under earthquake load. A simple model of 2 DOF spring-mass (see Figure 6a) is used to represent modeling of building with the introduced damper. The damper practically is inserted between the upper and lower structure of the building. There are several assumptions taken related to the parameters of dynamic of the model, as written below:

- Mass of the upper structure and lower structures are assumed $m_{2}=42741.7$ kg and $m_{1}=213708.68$ kg respectively.
- The stiffness $k_{2}$ is taken from the result of the static analysis, based on the following conditions: (a). if $x_{2}<\delta_{1}$, then $k_{2}=k_{i}$, then (b). If $x_{2}<\delta_{2}$, then $k_{2}=k_{II}$, finally (c). If $x_{2}<\delta_{3}$, then $k_{2}=k_{III}$. Moreover, the stiffness $k_{1}$ is assumed 22510.92 N/mm. It is calculated using the equation $k_{1} = m_{1} \omega_{1}^{2}$ by assuming $\omega_{1}=0.32$ Hz.
The damping value of $c_2$ is also taken from the result of the static analysis, while the damping value of $c_1$ is calculated by equation $c_1 = \xi_1 \times 2 \times \sqrt{k_1 m_1}$ using $\xi_1=0.5$.

All parameters are presented in Table 4.

![Figure 8](image-url) Deformation of U-shaped steel damper models under loading, (a) Model_01 (upper), (b) Model_02 (middle), Model_03 (lower)

| Model | $k_{I}$ (N/mm) | $k_{II}$ (N/mm) | $k_{III}$ (N/mm) | $c_2$ (N.s/mm) | $m_2$ (kg) | $k_1$ (N/mm) | $\xi_1$ | $m_1$ (kg) |
|-------|----------------|----------------|------------------|----------------|------------|--------------|--------|------------|
| 01    | 8975.96        | 3492.53        | 572.22           | 23203.10       | 42741.7    | 22510.92     | 0.5    | 213708.68  |
| 02    | 10582.00       | 4199.84        | 1274.39          | 27980.30       | 42741.7    | 22510.92     | 0.5    | 213708.68  |
| 03    | 18960.15       | 8178.98        | 4807.83          | 58710.80       | 42741.7    | 22510.92     | 0.5    | 213708.68  |

Then, a model of 1 DOF spring-mass (see Figure 6b) which represent modeling of the building without a damper is also used as a comparison. The dynamic parameters are presented in Table 5. Here, the total mass is equal to the summation of $m_1$ and $m_2$.

| Model | $k_1$ (N/mm) | $\xi_1$ | $m_1$ (kg) | $m_2$ (kg) |
|-------|--------------|--------|------------|------------|
| 1 DOF | 26984.7      | 0.05   | 213708.6   | 42741.7    |

The comparison of the displacement of the upper structure for the model with damper and without a damper is given in Figure 10. For 2 DOF model, this figure shows that, at $t=2$ seconds, the earthquake
load is the heaviest one, therefore when the maximum load is reached, the occurred displacement is around 25 mm. This deformation has passed the yielding point. It means that, only in 2 seconds, the U-shaped plate has been plastically deformed. The stiffness is changed from elastic stiffness $k_1$ to $k_2$ and then from $k_2$ to $k_3$ very rapidly. After 2 seconds, the cured plastic displacement then will be fluctuated around $\delta=10$ mm (the residual plastic deformation). Moreover, although the damping values of three introduced models are different from each other, however, the occurred displacements of the upper structure are almost similar among these models. It means that the differences of the damping values of the introduced models are still not significant enough to affect the displacement of the upper structure under the earthquake.

On the other hand, for 1 DOF model (the model of building without damper), the occurred displacement are fluctuated symmetrically at $\delta=0$ mm. The upper structure is displaced elastically due to the elastic stiffness. The maximum displacement shown on this figure is around 16 mm.

![Figure 9](image.png)

**Figure 9.** Comparison of the response of the displacement of the roof structure of all preentged models

4. Conclusion

This paper discusses a numerical analysis of a U-shaped steel damper which is subjected to a cyclic horizontal load in a variety of geometries of the slender column as a part for absorbing energy. Some points that can be concluded from this paper are:

1. The application of a slender column can be used to absorb the energy of the earthquake. This can be seen from the area of energy dissipation of Model_03 and Model_02 are larger than Model_01.
2. The sizes of the slender column will affect the energy dissipation. This can be seen from the area of energy dissipation of Model_03 is larger than Model_02.
3. The application of stiffness model in the form of a trilinear relationship gives a better result because this approach is considered similar to the practical condition.

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