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Cyclic Performance of an Elliptical-Shaped Damper with Shear Diaphragms in Chevron Braced Steel Frames

Seyed Mehdi Zahrai and Mohamad Hosein Mortezagholi
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ABSTRACT
Several advantages of yielding dampers in controlling seismic energy have attracted the attention of many researchers in designing new buildings and retrofitting existing structures. In recent decades, various shapes and substances of such dampers have been used in engineering structures and their behavioral features, including the energy dissipating capacities, have been assessed. In this article, a novel method is presented to obtain the design relationship of two types of yielding elliptical dampers in terms of their selected geometric properties, i.e. distance between the shear diaphragms or virtual diameter and thickness. In addition, two different elliptical-shaped steel dampers equipped with the shear diaphragms are proposed and modeled using the finite element software ABAQUS and their performances are investigated. Then, 30 and 25 models, respectively, of the first and second types are studied using pushover analysis. The designed dampers considering the proposed relationships are used in two chevron braced steel frames placed between the bracing and the beam. Due to their desirable efficiency in energy dissipation and increase in the equivalent viscous damping of the frame, better efficiency is achieved in the modified damper with easier fabrication.

1. Introduction
One main structural and seismic engineering problem which is of utmost importance is to find solutions for reducing forces exerted upon the main structural members. During an earthquake, a huge amount of energy is imposed on the structure. In structures which are designed using conventional methods, the plastic deformations of portions of the structure, such as connections, would cause partial energy dissipation. However, structural failure might occur due to damage in main members when the amount of input energy exceeds the structure capacity. In the case that the induced damages are local, they do not lead to collapse but the high cost of reconstruction becomes problematic. Hence, providing devices and systems which could prevent damage to the main structural members by absorbing the input energy is essential. The seismic isolators reduce the input energy to the structure in the event of an earthquake, and utilizing active, semi-active and passive control devices would increase the damping capacity of structure by dissipating the imposed seismic energy.
Passive dampers of various types are suitable for application in special types of structures, according to their functionality. Among passive dampers, steel yielding dampers due to lack of need for external sources, ease of their installation before and after the earthquake, and economic advantages have been widely studied. Experiencing the plastic behavior and concentrated damage, these dampers reduce the dynamic response of the structure while the main members remain in the elastic range. Kelly et al. [1972] proposed the application of yielding dampers in the structures. The X-shaped plates (ADAS) [Whittaker et al., 1991] and the triangular plates (TADAS) [Tsai et al., 1993] comprised of steel plates between two rigid plates, the Buckling Restrained Braces with their significant ductility [Benavent-Climent et al., 2011; Hoveidae et al., 2015] and the J-shaped damper dissipating energy through rolling-bending movement [Kato et al., 2005] are some examples of steel yielding dampers. The steel rhombic-shaped damper (RADAS) made of two connected triangular plates was studied by Ming-hsiang et al. [2004]. The fundamental mechanical features and energy-dissipation capacity of this kind of damper were later examined by Han et al. [2014].

Williams and Albermani [2006] introduced the yielding shear panel device as the passive damper, consisting of a thin diaphragm steel plate welded inside a square hollow section. This damper dissipates energy through in-plane shear yielding of its diaphragms. Chan et al. [2009] investigated the yielding shear panel experimentally and found that the slenderness of diaphragm and the surrounding in-plane stiffness of this damper are effective on its performance. Hossain et al. [2011] developed the finite element model for this damper in ANSYS software utilizing material and geometric nonlinearities. Li et al. [2011] developed the technique of Bouc–Wen–Baber–Noori (BWBN) hysteretic model for considering the pinching and degradation effects in the modeling of yielding shear panel device. The hysteretic behavior of the low-yield-strength steel shear panel damper was evaluated by Zhang et al. [2013] through static and dynamic experimental work.

Deng et al. [2015] proposed a novel SPD called Buckling Restrained Shear Panel Damper. This damper was made of an energy-dissipation plate and two external restraining plates. The tests showed that if restricted plates have sufficient stiffness and strength, the out-of-plane buckling of the energy-dissipation plate can be prevented. The shear-flexural yielding steel dampers [Sahoo et al., 2015] which are a combination of shear link plates and two X-shaped dampers at their end have been recently studied both experimentally and numerically. Zahrai [2015] has experimentally assessed the vertical link beam as another type of yielding damper. The test specimens from IPE sections (sections with narrow thickness flanges) showed high ductility and nearly dissipated the whole input energy while other components remained in the elastic zone.

Maleki and Bagheri [2010] have proposed the pipe damper, filled and unfilled with concrete subjected to cyclic shear loading. Their results indicated that the hollow pipes due to appropriate ductility in comparison with the concrete-filled pipes have greater capability of energy dissipation. In order to improve the performance of this kind of damper, the infilled pipe damper [Maleki and Mahjoubi, 2014], consisting of two welded pipes in which two smaller pipes were placed and the inner space was filled by Plumb or Zink, was presented. Afterward, Najari [2014] numerically assessed the elliptical-shaped damper in the chevron braced frame. It was found that using this type of damper with different diameters and thicknesses, the structure elements remain in the elastic zone. Therefore, by considering increase in ductility and also proper energy dissipation in the structure, the proposed damper
could be utilized to improve the seismic behavior of steel frames. Therefore, by considering 
increase in ductility and also proper energy dissipation in the structure, the proposed damper 
could be utilized for increasing the seismic resistance of steel frames. Abebe and Choi [2014a] 
have developed and assessed the structural performance of both cases of stiffened and non-
stiffened Circular Shear Panel Damper (CSPD) and Slit Circular Shear Panel Damper (SCSPD) [Abebe and Choi, 2014b]. The results showed that the cumulative plastic deforma-
tion of the SCSP damper is much higher than that of the Circular Shear Panel (CSP) damper 
and for this reason it exhibits better performance in absorbing the seismic energy.

In this paper, the performance of two types of elliptical-shaped dampers with shear 
diaphragms in chevron braced steel frames is investigated using the ABAQUS software. The 
first type of damper is made of a segment with elliptical cross section and two shear 
diaphragms, each placed on either side, while the second type has a quasi-elliptical structure 
and easier fabrication. Since appropriate design of a yielding damper would significantly 
affect its efficiency, a relationship is derived for the damper design in terms of specific 
geometric properties. This is conducted after comparing the experimental and numerical 
results and ensuring the validity of the model using the ABAQUS software. The geometric 
properties are: distance between the shear diaphragms and the damper thickness for the first 
type and virtual diameter and the damper thickness for the second type of damper. It should 
be noted that in every design relationship, numerous geometric and non-geometric para-
meters could be involved and considering them all in the relationship makes it complex for 
practical application. However, the ultimate goal of design is not to obtain maximum shear 
force of a damper with distinct parameters for which there would be a need to involve all 
parameters in the relationship. In order to obtain a distinct shear force less than the bracing 
capacity, it is intended to determine some of the influencing geometric parameters while 
other parameters are considered constant. So, the application of two influencing geometric 
parameters to achieve this goal is justified. Due to investigating the effect of variation just in 
two geometric parameters of the damper, and lacking a known mathematical relationship 
between the geometric properties and the ultimate capacity of the dampers also to improve 
the reliability of the obtained relationship within a wider range of variations in the geometric 
dimensions, there is a need to consider an acceptable number of dampers. Therefore, to 
extract the design relationship for the first and second types of the damper, pushover 
analyses of, respectively, 30 and 25 models are performed. 

Finally, the cyclic performance of the designed dampers is assessed on two different 
types of frames to investigate the appropriateness of the proposed relationship.

2. Elliptical and Modified Elliptical-Shaped Dampers with Shear diaphragms

In this study, two types of dampers are investigated and their fabrication and the range of 
their dimensions are explained subsequently.

2.1. Elliptical-Shaped Damper with Shear Diaphragms

Elliptical-shaped damper with shear diaphragms is comprised of a horizontal elliptical-
shaped profile with two lateral shear diaphragms. The application of an elliptical-shaped 
component instead of the pipe profile provides more freedom in the design of the damper. 
For example, for each constant eccentricity we could design a damper with higher energy-
dissipation capacity just by changing the major diameter of the ellipse, while in the case of pipe profile to attain this property there would be a need for two profiles with parallel connections. Also in continuation, by placing an elliptical-shaped component with or without shear diaphragms in one of the examined frames, it could be demonstrated that the application of shear diaphragms, due to reduced local buckling in the elliptical-shaped component, would result in increased efficiency of the damper. Their variable geometric parameters are the distance between the shear diaphragms \( L \) and the thickness of damper \( t \). The thickness of the elliptical-shaped segment and the shear diaphragms are equal in each of the models (Fig. 1). The range of distance between the shear diaphragms of the damper is 10–30 cm (with steps of 5 cm) and its thickness is in the range of 0.25–1.50 cm (with steps of 0.25 cm) as presented in Table 1.

This range of variations for geometric properties of the damper is considered to achieve a capacity close to those of the conventional bracing systems. In this type of damper, the major, external, diameter is taken as 30 cm and the minor, internal, diameter is taken as 15 cm. This damper is named in the form of EDLntm, in which ED is abbreviated for Elliptical Damper, L stands for “Length,” \( n \) is the distance between the shear diaphragms in cm, \( t \) stands for “thickness” and \( m \) is the thickness of damper in cm. For example, EDL25t1 introduces an elliptical-shaped damper with 25 cm length and 1 cm thickness (Fig. 2).

### 2.2. Modified Elliptical-Shaped Damper with Shear Diaphragms

Modified Elliptical-Shaped Damper with shear diaphragms is made of a quasi-elliptical segment with two shear diaphragms (Fig. 3). As observed from the results of elliptical-shaped damper with the shear diaphragms, the distance between shear diaphragms in design relationship of the damper is not an effective factor in design process. So in the modified model, in addition to ease of damper fabrication at the site, the distance between

---

**Table 1. Characteristics of damper type 1.**

<table>
<thead>
<tr>
<th>Behavioral characteristics of steel</th>
<th>Geometric parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield stress 240 MPa</td>
<td>Constant</td>
</tr>
<tr>
<td>Tensile strength 370 MPa</td>
<td>Parameter name</td>
</tr>
<tr>
<td>Elongation rate 0.2</td>
<td>Parameter value</td>
</tr>
<tr>
<td>Parameter name</td>
<td>Range changes (cm)</td>
</tr>
<tr>
<td>Small diameter (cm) 15</td>
<td>Distance between shear diaphragms (( L )) 10–30</td>
</tr>
<tr>
<td>large diameter (cm) 30</td>
<td>Thickness (( t )) 0.25–1.50</td>
</tr>
</tbody>
</table>
shear diaphragms is replaced by virtual diameter parameter for the purpose of enhancing effectiveness (Fig. 4). In this case, the distance between shear diaphragms is taken as a constant value equal to 10 cm. The small distance taken between the shear diaphragms for type 2 damper is to facilitate installation to a narrow beam. The geometric parameters include the virtual diameter of ellipse with a range of 10–30 cm (with steps of 5 cm) and the thickness of damper with a range of 0.5–1.5 cm (with steps of 0.25 cm) as presented in Table 2.

The obtained results for type 1 damper reveals its reduced performance due to the premature local buckling in models with small thicknesses. Therefore, with respect to type

Figure 2. Elliptical damper: (a) schematic view; (b) longitudinal section; and (c) cross section.

Figure 3. Modified elliptical shaped damper with shear diaphragms.

Figure 4. Modified elliptical damper: (a) schematic view; (b) longitudinal section; and (c) cross section.
2 damper, those models with thicknesses of 0.25 cm have been removed. The reason for application of virtual diameter term is due to the quasi-elliptical shape of the damper and impossibility to define the major and minor diameters like a real elliptical section. Naming various models of quasi elliptical damper is also indicated in the form of MEDDntm, in which MED is abbreviated for ‘Modified Elliptical Damper’, D stands for “Diameter,” n is the virtual minor diameter in cm, while t and m have a similar definition as explained in the previous section. For example, a modified elliptical damper with a virtual minor diameter of 25 cm and thickness of 1 cm, is named as MEDL25t1.

3. Modeling Details

Solid elements in 3D space are used for modeling. The material behavior curve used by considering the effects of hardening steel is elasto-plastic. Assuming that the loading is gradual and slow, the effects of velocity and acceleration are negligible and therefore the type of analysis is in general static. Also, the secondary effects due to the large deformations and buckling of the members are considered in the analysis process. The interaction between all structural members is such that all degrees of freedom are translated to the connection levels. The elements used in this study are 8-node brick elements with reduced integration, in which the hourglass effects are controlled (C3D8R). For validation of the numerical method, the number of used meshes in the analysis problem is increased in a few stages (the meshing size is halved) and distribution of one of the variables is taken into account. The proper size of meshes is obtained when the change in size would lead to less than 10% difference, corresponding to reasonable accuracy and processing cost.

4. Numerical Model Validation

Since the experimental results of the chevron braced steel frame with elliptical-shaped cross-section link beam are not available, an experimental work of I-shaped vertical link beam in a chevron braced steel frame is considered. The finite element software ABAQUS is used for numerical modeling of SPS2 and SPS4 test specimens [Zahrai, 2015] as shown in Fig. 5. A comparison of the numerical and experimental results confirms the accuracy of modeling the main components of chevron braced frames, the connections, boundary conditions, and the applied loads. Also due to the appropriate compliance observed between the results, one could conclude the accuracy of dimension choice and shape of the applied meshing. The difference between the numerical and experimental models was caused by ignoring details of the welded and bolted connections in the numerical model.

Table 2. Characteristics of damper type 2.

<table>
<thead>
<tr>
<th>Behavioral characteristics of steel</th>
<th>Geometric parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Behavioral characteristics</strong></td>
<td><strong>Constant</strong></td>
</tr>
<tr>
<td>Yield stress 240 MPa</td>
<td>Distance between shear diaphragms(L) (cm)</td>
</tr>
<tr>
<td>Tensile strength 370 MPa</td>
<td>10</td>
</tr>
<tr>
<td>Elongation rate 0.2</td>
<td>Virtual Large diameter(cm)/ virtual small diameter (cm)</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td><strong>Variable</strong></td>
<td><strong>Parameter name</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Parameter value</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Range changes (cm)</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Step changes (cm)</strong></td>
</tr>
<tr>
<td>Distance between shear diaphragms(L) (cm)</td>
<td>10</td>
</tr>
<tr>
<td>Virtual Large diameter(cm)/ virtual small diameter (cm)</td>
<td>10–30</td>
</tr>
<tr>
<td>Thickness (t)</td>
<td>Virtual diameter (D)</td>
</tr>
<tr>
<td></td>
<td>0.5–1.5</td>
</tr>
<tr>
<td></td>
<td>Thickness (t)</td>
</tr>
<tr>
<td></td>
<td>0.5–1.5</td>
</tr>
</tbody>
</table>

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These details appear to be negligible due to the small difference in the performance curves, as shown in Fig. 6.

ST37 steel was used for the main members of the frames. The yield stress ($F_y$) and ultimate stress ($F_u$) of the vertical link beam (VLB) were 3372 and 4822 for SPS2,
respectively. These values for SPS4 are 3641 and 5175, respectively. In addition, the geometric properties of the frames and VLBs are presented in Table 3. In the following, cyclic curves obtained from the numerical and experimental results are compared. It should be noted that due to the gradual loading of the experimental model according to the AISC2010 code, the effects of acceleration and velocity are negligible. Therefore, in the numerical model, the static analysis is incorporated.

5. Proposing Design Relationship

As one main objective of damper design is to limit the level of forces induced in the braces, in order to derive the maximum producible shear force by the dampers, all of the 30 elliptical-shaped dampers and 25 modified dampers with appropriate boundary conditions are analyzed using the pushover analysis method. To prevent braces from buckling and achieve accurate design of dampers with a good approximation, it is assumed that the damper lower plate is anchored as fixed. Also due to the high axial stiffness of the column, the beam connected to the damper prevents downward movement of the upper plate and finally the lateral movement of the beam causes displacement in the damper upper plate. Accordingly, the equivalent boundary condition for pushover analysis of the damper is shown in Fig. 7. To draw the pushover curve, a displacement of about 4% of the conventional frame's height (3 m) is applied to the dampers. The pushover curves of the whole models are presented in the appendix.

<table>
<thead>
<tr>
<th>Frame</th>
<th>Member</th>
<th>Column</th>
<th>Beam</th>
<th>Brace</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPS2</td>
<td>Section</td>
<td>IPB120</td>
<td>IPB140</td>
<td>2UNP80</td>
</tr>
<tr>
<td></td>
<td>Length (cm)</td>
<td>300</td>
<td>420</td>
<td>345</td>
</tr>
<tr>
<td>SPS4</td>
<td>Section</td>
<td>2IPE140</td>
<td>IPE180</td>
<td>2UNP80</td>
</tr>
<tr>
<td></td>
<td>Length (cm)</td>
<td>300</td>
<td>420</td>
<td>337</td>
</tr>
<tr>
<td>VLB</td>
<td>Shear panel</td>
<td>Stiffener</td>
<td>Thickness</td>
<td>1</td>
</tr>
<tr>
<td>SPS2</td>
<td>Section</td>
<td>IPE140</td>
<td>Thickness</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Length (cm)</td>
<td>20</td>
<td>Distance</td>
<td>10</td>
</tr>
<tr>
<td>SPS4</td>
<td>Section</td>
<td>IPE140</td>
<td>Thickness</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Length (cm)</td>
<td>30</td>
<td>Distance</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 7. Equivalent boundary conditions: (a) the lower plate of damper and (b) the upper plate of damper.
maximum shear force induced in each pushover curve is an appropriate approximation of this controlling force. After determining the necessary curves for the models, the maximum induced shear force is determined. For example, using the pushover curves of EDL10t1.5 and EDL20t1 models, the maximum shear force of the dampers is obtained as 1676.42 and 1034.56 kN, respectively (Fig. 8). This process is conducted for all pushover curves and the results are shown in Tables 4 and 5 for each type of damper.

In Fig. 9 the yielded zones of the damper due to applying final displacement are shown to highlight the yielded elements for two cases: type1 and type2 dampers, so that each element after yielding is shown with number 1 and red color (dark parts) and in case of not yielding is shown with number zero and blue color (light parts). As observed, the major dissipated energy in these dampers resulted from the yielding of the shear diaphragms (Fig. 9).

The maximum shear force is a function of geometric parameters of dampers (distance between shear diaphragms and thickness for the ED and virtual diameter for the MED). In the first step, to obtain the intended design relationship between two available geometric parameters for each damper, the thickness is taken as a constant and the maximum shear force is expressed in terms of the other parameters (Fig. 10).

<table>
<thead>
<tr>
<th>Table 4. Maximum shear forces for elliptical dampers.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
</tr>
<tr>
<td>--------</td>
</tr>
<tr>
<td>EDL10 t 0.25</td>
</tr>
<tr>
<td>EDL10 t 0.5</td>
</tr>
<tr>
<td>EDL10 t 0.75</td>
</tr>
<tr>
<td>EDL10 t 1</td>
</tr>
<tr>
<td>EDL10 t 1.25</td>
</tr>
<tr>
<td>EDL10 t 1.5</td>
</tr>
<tr>
<td>EDL15 t 0.25</td>
</tr>
<tr>
<td>EDL15 t 0.5</td>
</tr>
<tr>
<td>EDL15 t 0.75</td>
</tr>
<tr>
<td>EDL15 t 1</td>
</tr>
</tbody>
</table>
Considering the location of points in the coordinate system, a line represents the best fitted curve for maximum shear force in terms of the distance between shear diaphragms and the virtual diameter for the ED and MED, respectively, and corresponding to a constant thickness.

Table 4 shows the equation of these lines and the coefficients of determination. The ‘determination coefficient’ $R^2$ is defined as follows:

$$R^2 = \frac{SSTO - SSE}{SSTO} \quad (1)$$

where SSTO and SSE are abbreviations of the Sum of Squared Total and Sum of Squared Error, respectively. Comparing the slope of the lines in Table 6, especially for small thicknesses, the increase in the sensitivity of the design relationship to the geometric parameter of virtual diameter of modified elliptical damper is well justified with respect to the distance between shear diaphragms of the elliptical damper.

The slope and intercept for each linear equation in the form $F_{max} = a(L or D) + b$ vary with thicknesses. Therefore, it could be concluded that the parameters $a$ and $b$ are both functions of the thickness. Considering the effect of the second geometric parameter (thickness) in the design relationship, the best fitting curve corresponding to the slope and intercept of the above lines are depicted with respect to the thickness. Figure 11 shows the best fitted curves for these parameters. Having obtained the equations corresponding to the parameters $a$ and $b$ by curve fitting and replacing them in the initial linear equation, the basic design relationships of the dampers are obtained as follows:

Figure 9. Yielded zones at maximum applied displacement: (a) EDL10t1 and (b) MEDD20t1.
**Table 6. Equations of the fitted lines.**

<table>
<thead>
<tr>
<th>Elliptical Damper</th>
<th>Thickness (cm)</th>
<th>Equation</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>( F_{ED}^{max} = 0.650L + 190.16 )</td>
<td>0.9708</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>( F_{max} = 1.668L + 397.42 )</td>
<td>0.9869</td>
<td></td>
</tr>
<tr>
<td>0.75</td>
<td>( F_{max} = 2.894L + 653.86 )</td>
<td>0.9802</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>( F_{max} = 5.750L + 923.05 )</td>
<td>0.9971</td>
<td></td>
</tr>
<tr>
<td>1.25</td>
<td>( F_{max} = 11.522L + 1207.75 )</td>
<td>0.9993</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>( F_{max} = 22.333L + 1446.04 )</td>
<td>0.9898</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Modified Elliptical Damper</th>
<th>Thickness (cm)</th>
<th>Equation</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>( F_{max} = 16.213D + 215.14 )</td>
<td>0.9954</td>
<td></td>
</tr>
<tr>
<td>0.75</td>
<td>( F_{max} = 20.032D + 357.31 )</td>
<td>0.9942</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>( F_{max} = 30.473D + 481.64 )</td>
<td>0.9979</td>
<td></td>
</tr>
<tr>
<td>1.25</td>
<td>( F_{max} = 36.849D + 633.56 )</td>
<td>0.9974</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>( F_{max} = 45.448D + 742.93 )</td>
<td>0.9962</td>
<td></td>
</tr>
</tbody>
</table>

\[
\begin{align*}
\begin{cases}
  a &= 19.184 t^2 - 17.478 t + 4.577, & \text{SSR} = 0.9872 \\
  b &= 1026.24 t - 94.911, & \text{SSR} = 0.9981
\end{cases} \\
\Rightarrow & \quad F_{max}^{ED} = aL + b \\
\Rightarrow & \quad F_{max}^{ED} = (19.184 t^2 - 17.478 t + 4.577)L + (1026.24 t - 94.911)
\end{align*}
\]

(2 – a)
Constant coefficients $a$ and $b$ of the studied dampers are a function of the geometric and non-geometric parameters which have not been incorporated in the design relationship. For example, by changing the type of steel used in the damper, the constant coefficients also have different values. In design-related issues, it is essential to identify the influential parameters and to subsequently investigate and assess them. The behavioral curve of the constituent material of the damper is among the effective factors in the design relationship. However, for each arbitrary behavioral curve one can obtain the design relationship of the elliptical-shaped damper based on a similar process. In this particular case, these coefficients are a function of the behavioral characteristics of the material used in damper. Also as shown in Fig. 12, it could be concluded that due to extreme similarity of the curves to each other, the distance between shear diaphragms is not an effective parameter and the related shear force especially in small thicknesses has negligible variation. Therefore, the distance between shear diaphragms of damper is not an influencing factor in design here.

Lack of sensitivity of maximum shear force with respect to the distance between shear diaphragms of the first type damper, especially for small thicknesses and increase in the sensitivity of second type damper with respect to the virtual diameter is well observable in the 3D diagram of Fig. 13a and b. For larger thicknesses, these variations become more

\begin{align*}
\begin{cases}
a = 29.315 t + 0.888, & \text{SSR} = 0.9962 \\
b = 532.73 t - 46.616, & \text{SSR} = 0.9980
\end{cases}

\Rightarrow F_{\text{max}}^{\text{MED}} = aD + b (2 - b)
\end{align*}
prominent. Also, the maximum shear force corresponding to the specified range would vary for geometric parameters of the first type damper in the range of 200–2000 kN and for geometric parameters of the second type damper in the range of 400–2000 kN. Note that due to the formation of linear terms with respect to the existing geometric parameters in the design relationships, reducing the number of models is possible such that even with four models, one can achieve these design relationships with good accuracy.

6. Assessment of the Proposed Design Relationship

6.1. ED

In order to install the elliptical-shaped damper in SPS4 test frame, with respect to selected diameters, it is necessary to change the length of braces. Lack of ability in changing the in-plane dimensions of this type of damper is among its basic design shortcomings. Hence in
In this section, the length of SPS4 frame braces is changed and the cyclic performance of the elliptical-shaped damper is examined. This modified frame is named SPS4′. The capacities of chevron bracings for SPS4′ and SPS4 frames in case of negligible yield and lack of buckling are about 625 and 255 kN, respectively. To determine the maximum base shear at the braces, one could put the upper gusset plate under a controlled displacement and obtain the maximum shear capacity before buckling. However, due to the distance between beam and gusset plate, the set of braces is not in fact subjected to a pure shear force and an additional moment is also applied to the setting which results in reduced bracing capacity.

Therefore, another method is used to determine real capacity of the set of braces. In this case as shown in Fig. 14, a reference point on the lower flange of the beam in the frames without dampers (SPS4 and SPS4′) is defined and three translational degrees of freedom at this point are transferred to the upper gusset plate. It is worth noting that due to axial stiffness of the columns, the beam connected to the damper prevents movement of the upper gusset plate downward or in other words restrains it in the vertical direction. Hence, to simulate the above conditions, the translational degree of freedom of reference point in the vertical direction is translated to the beam. Next, the reference point would be subjected to a controlled displacement. This displacement continues as long as the compressive brace has not buckled, meanwhile a negligible yield occurs in the set of braces and the gusset plates. Finally, the maximum base shear of the bracing before buckling and yielding would be selected as the capacity of the bracing. It should be noted that the aforementioned method is the idea of the authors, consistent with other methods to determine the bracing capacity.

But in this method using the computer facilities, other details like effects of the axial stiffness of columns and the extra moment due to eccentricity of the bracing are considered in the accurate determination of the bracing capacity.

In the following section, by considering the SPS4′ frame, the chevron bracing capacity and the obtained design relationship, the geometric dimensions of the elliptical-shaped damper are determined. Considering the width dimension of the beam in the SPS4′ frame (9.1 cm), the geometric parameter of distance between shear diaphragms of damper is taken as 9 cm.

\[
F_{\text{max}}(t, L) = (19.184 t^2 - 17.478 t + 4.577)L + (1026.24 t - 94.911)
\]
\[
F_{\text{max}}(t, 9) = 625 \quad \Rightarrow \quad t \approx 0.68 \text{ cm}
\]
After determining the geometric dimensions of the damper, its cyclic performance within the SPS4′ frame is assessed. Considering the bi-linearization of the force-displacement diagram, the equivalent yield displacement of the frame is estimated to be 0.6 cm as shown in Fig. 15 where, V is the base shear, \( V_y \) is the yield shear force, and Drift is the ratio of relative lateral displacement to the frame height. Fig. 16 shows the time history of cyclic loading and the cyclic hysteretic curves.

Finally, the energy dissipation due to plastic behavior is shown in Fig. 17. From the dissipated energy diagram for ED with respect to the whole frame, it could be concluded that:

A: For six initial cycles, all structure members remained in the elastic zone and the input energy to the structure is stored like an elastic spring.

B: For the three next cycles, almost all energy dissipation takes place in the damper and main members like the beam, braces, and columns remain within the elastic range.

C: Afterwards, the main members of the structure together with the damper participate in the dissipation of input energy to the structure. In this case, 76% of the energy is dissipated through yielding of the damper.

\[
\text{Efficiency up to Cycle 23} = \frac{\text{PDE for Damper}}{\text{PDE for Frame}} = \frac{206.7340}{272.0750} = 0.76
\]

Figure 15. Force-displacement curve of SPS4′ frame equipped with ED.

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Figure 16. (a) Loading protocol and (b) cyclic hysteretic curves of SPS4′ frame equipped with ED.
where PDE is the abbreviation for the Plastic Dissipated Energy.

Design of the ductile member is implemented properly when not only such member dissipates the main part of the energy imposed to its structure, but also as a fuse prevents damage to the main structure members such as braces. The results obtained from both the introduced dampers indicate the proper performance of the ductile members and meet the above-mentioned conditions.

Using the elliptical-shaped profile without shear diaphragms in chevron bracing does not induce acceptable energy dissipation in the system due to instability and premature buckling and it could be stated that the set of damper and chevron bracings does not affect the seismic performance of the structure, while utilizing shear diaphragms in the elliptical-shaped damper could significantly increase the efficiency. For example, in Fig. 18, which demonstrates the energy dissipation by a damper having no shear diaphragm compared to the whole frame, no force is induced in the set of damper and bracing due to the buckling of the elliptical-shaped plates and as a result there would be no significant energy dissipation.

But, the addition of shear diaphragms to the set not only prevents buckling of the elliptical-shaped segment but also the major portion of this energy is dissipated through yielding of these shear diaphragms. It is worth noting that shear diaphragms are actually considered as the main yielding members in the ductile element and the elliptical-shaped component has the role of constraining these lateral plates. As a result, the effective role of these lateral plates becomes more significant as shown in Fig. 19.

### 6.2. MED

In order to determine the geometric dimensions of the modified elliptical-shaped damper with respect to the amount of eccentricity and the capacity obtained from chevron bracings in both SPS4 and SPS4’ frames considering expression (2-b), appropriate dimensions of the damper are derived in each case.

\[
F_{\text{max}}(t, D) = (29.315 t + 0.888)D + (532.73 t - 46.616)
\]

\[
F_{\text{max}}(t, 30) = 255 \quad \Rightarrow \quad t \simeq 0.2 \, \text{cm} \quad (5 - a)
\]

\[
F_{\text{max}}(t, D) = (29.315 t + 0.888)D + (532.73 t - 46.616)
\]

\[
F_{\text{max}}(t, 15) = 625 \quad \Rightarrow \quad t \simeq 0.67 \, \text{cm} \quad (5 - b)
\]
In SPS4 frame, the longitudinal dimensions of the damper are very large (virtual major
diameter 60 cm, virtual minor diameter 30 cm) and its thickness is very small (0.20 cm).
Note that 0.20-cm thickness is obtained by extrapolating the design relationship with
respect to the range defined for geometric parameters of the damper. So in this model, not
only the extrapolation method is investigated in the determination of geometric dimen-
sions of the damper but also the performance of the shear diaphragms with large
dimensions and small thickness is examined. By placing the damper within SPS4 and
SPS4’ frames and performing pushover analysis, the force-displacement curve as shown in
Fig. 20 determines the yield displacements for both frames to be 0.60 and 0.70 cm,
respectively.

Considering the yield displacement, the time history of the loading protocol with a
domain of 7 times the yield displacement is shown in Fig. 21.

Figures 22 and 23 show the cyclic curves and the rate of energy dissipation for the
damper with respect to the whole frame, respectively, each for SPS4 and SPS4’ frames.

Considering the energy-dissipation diagram for the damper and the whole frame, the
following results are derived:

![Figure 18. Energy dissipation in damper with no shear diaphragms compared to that of the whole SPS4’ frame.](image)

![Figure 19. (a) Yielded zones for elliptical damper with no shear diaphragms and (b) yielded zones for damper with shear diaphragms.](image)
A: For nine initial cycles, all structure members remained in the elastic zone, which means zero energy dissipation in the whole frame.

B: For the next three cycles in both models, due to negligible difference between the two curves, all energy dissipation is due to inelastic behavior of the damper.

Figure 20. Normalized force-displacement relationships for the frames equipped with MED: (a) SPS4 and (b) SPS4’.

Figure 21. Lateral loading protocol applied to the frame equipped with MED: (a) SPS4 and (b) SPS4’.

Figure 22. Cyclic curves of the frame equipped with MED: (a) SPS4 and (b) SPS4’.
C: In the remaining cycles, due to imposing the main members to the plastic range, the performance of the damper is reduced so that its efficiency at the end of loading is the same for both models:

SPS4 frame

$$\text{Efficiency up to Cycle 23} = \frac{\text{PDE for Damper}}{\text{PDE for Frame}} = \frac{140.468}{155.560} = 0.94$$  \hspace{1cm} (6)

SPS4’ frame

$$\text{Efficiency up to Cycle 23} = \frac{\text{PDE for Damper}}{\text{PDE for Frame}} = \frac{248.999}{359.772} = 0.69$$  \hspace{1cm} (7)

Similar to the elliptical-shaped damper, addition of shear diaphragms to the quasi-elliptical segment significantly increases its efficiency (Figs. 24 and 25).

7. Equivalent Viscous Damping

The inherent damping in the structures under factors such as the friction between the members, looseness of the connections, and material degradation for the steel structures ranges between 2% and 5%. Application of energy dissipation devices in these structures would result in a significant increase in the damping ratio. This damping is non-linear and
induces complexities in the process of analysis. In order to reduce these complexities, the non-linear damping concept is replaced by the equivalent viscous damping concept. By setting the dissipated energy by non-viscous damping equal to the damping of a viscous material, the amount of equivalent viscous damping is obtained.

Considering Fig. 26, the equivalent viscous damping ($\xi_{eq}$) would be [Priestly et al., 1996]:

$$\xi_{eq} = \frac{A_h}{2nV_m\Delta_m}$$  \hspace{1cm} (8)

In which $A_h$ is the area under the curve, $\Delta_m$ and $V_m$ are the mean maximum displacement and shear force in a complete cycle of the cyclic curve, respectively. The equivalent viscous damping for the last cycle of the cyclic loading curve for the three tested models are given in Table 7.

As presented in Table 7, the last cycle damping for all models is in the range of 28–32% which indicates effective performance of the elliptical dampers.

Figure 24. Energy dissipation rate for the damper with no shear diaphragms with respect to the whole SPS4 frame.

Figure 25. (a) Yielded zones for the modified elliptical damper with no shear diaphragms and (b) yielded zones for the damper with shear diaphragms.
8. Conclusion

To propose new yielding dampers, in this paper two types of dampers with elliptical cross section were studied. By modeling 30 elliptical dampers and 25 modified elliptical dampers and with variable geometric parameters and performing pushover analysis, the design relationships with simple and accurate formulation were obtained for the proposed yielding dampers.

By designing the proposed dampers based on the presented relationships and placing them into the chevron braced steel frames and also examining the cyclic performance of the set of frame and damper in dissipating energy and increasing the damping ratio, the assessment of the design relationships was carried out. The results indicate the appropriateness of the design relationships because in addition to significant energy-dissipation share by the elliptical damper, such a device acts like a fuse and prevents the braces from buckling or yielding by controlling the force level. Investigating the cyclic performance of the elliptical-shaped component placed in the chevron braced frame with or without shear diaphragms, reveals the effective role of such diaphragms in improving the performance of the ductile member. It should be mentioned that after assuring of the appropriate performance of the elliptical-shaped component with the shear diaphragms, the second generation of this damper was recommended for practical purposes.

As a primary step for any complementary study and experimental work, design relations for the proposed dampers were developed in this paper. In addition, the described regression analysis method is not limited to the proposed energy dissipation system and can be used for defining design relations of other dampers.
References


Appendix

Pushover curves of dampers type I and type II with respect to geometric parameters are shown in Figs. A1 and A2, respectively.

Figure A1. First damper: (a) L = 10, (b) L = 15, (c) L = 20, (d) L = 25, and (e) L = 30.
Figure A2. Second damper: (a) D = 10, (b) D = 15, (c) D = 20, (d) D = 25, and (e) D = 30.