Evaluation of the energy dissipation capacity of a steel damper

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Abstract. This paper demonstrates the evaluation of the energy dissipation capacity of a steel damper made from mild steel plates through performing a finite element analysis simulating cyclic loading. Results aimed to obtain the damper characteristics incorporated in retrofitting frames to increase their seismic resistance and energy dissipation. The analysis has well captured the damper energy dissipation capacity and the effective stiffness. Results showed that stresses were concentrated on the diaphragm plate since it is the weakest part of the damper and where the failure is expected to occur. Also, the diaphragm plate was the first segment of the damper to yield and enter the plastic ranges.

1 Introduction

Earthquakes are considered one of the major causes of building damages and life losses, and it is challenging to protect structures from such natural disasters. The main cause of the structural damages is the energy transferred from the ground motion to the structure and the structural elements. Many seismic control systems are to be applied to structures, such as seismic resistance systems, seismic isolation systems, and seismic damping systems, which absorb the energy coming to the structure and can be replaced after the earthquake over and the device is damaged. This method is not expensive compared to the other methods, and it is easy to replace the device when it is damaged [1].

Currently, energy dissipation links and frame beams are designed as one whole body, making the replacement process after the link is damaged very difficult, expensive, and time-consuming. In recent years, replaceable energy dissipation links have been proposed by many researchers along with other types of energy dissipation devices to solve the deficiencies of unreplaceable devices. Yin et al. [2] performed an experimental study by designing the energy dissipation link as an independent component, separated from the

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frame beam. The experimental output showed that the energy dissipation of the web-connected link has good ductility and stable energy dissipation ability. The energy dissipation capacity of the shear connection is better than the capacity of the curved link. The failure mode of the finite element analysis and the test specimens are similar.

Kim and Kim [1] concluded that any change in the shape of the connecting member will have no major degradation in the structural performance. Teruna et al. [3] showed that the Bauschinger part of the specimens consumed more than 80% of the total plastic energy. The elastic stiffness, yield force, and the first and second postyield stiffness can approximate the skeleton curves by using a tri-linear model. Matteis et al. [4] showed that the use of pure aluminum shear panels (PASPs) delayed the first damage of the frame members at inter-story drift ratios higher than one corresponding to the service limit state.

One of the replaceable devices is the energy dissipation steel damper proposed in this study, as it was not used in any previous research, and it is a unique device with an irregular shape. The damper will be constructed out of mild steel, and it will be bolted directly to the beam and column, wherein previous studies, connectors like hinges are used to connect the damper to the structure.

The main objective of this paper is to evaluate the proposed steel damper by performing Finite Element Analysis (FEA) to get the properties of the damper, such as the effective stiffness and the damping ratio. The finite element analysis will be carried out using Ansys Workbench software, which will be used to simulate a cyclic loading that will be applied to the damper, resulting in the hysteretic behavior and the desired parameters.

2 Geometry and material properties

2.1 Damper geometry

The damper consists mainly of seven plates, two end plates, two intermediate vertical plates to act as extra support to the damper, one diaphragm plate, and two plates for the bottom and top sides of the damper. The top and bottom plates have a uniform width with a semi-circular reduction in the width at the middle of the damper. Figure 1 shows a 3D representation of the damper.

Fig. 1. 3D Representation of the damper.

Two thicknesses are mainly used in the damper, 2 mm for the diaphragm plate and 6 mm for the top plate, the bottom plate, the vertical support plates, and the endplates (less thickness for the diaphragm plate to make it the weakest part of the damper). The dimensions of the damper (in mm) are illustrated in Figure 2.
The damper is designed in a curved shape at the frames’ two-column beam junctions (to provide more connection at the edges of the frame). Figure 3 shows the configuration of the steel dampers bolted to a steel frame (figure not to scale).

2.2 Material properties

The mechanical properties of the steel are essential to know for use in analytical analyses. Table 1 summarizes the mechanical properties of the steel obtained from a testing database [5].

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>7850</td>
</tr>
<tr>
<td>Modulus of Elasticity, E (GPa)</td>
<td>195</td>
</tr>
<tr>
<td>Yield Strength, σ_y (MPa)</td>
<td>290</td>
</tr>
<tr>
<td>Ultimate Strength, σ_u (MPa)</td>
<td>460</td>
</tr>
<tr>
<td>Poisson’s Ratio, ν</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 1. Mechanical properties of the mild steel [5].
In order to obtain the hysteretic behavior, the material plasticity must be defined to ensure that the damper will enter the plastic region. Several plasticity models are available on the Ansys Workbench software database, such as Bilinear Isotropic Hardening, Multilinear Isotropic Hardening, Chaboche Kinematic Hardening, etc. However, some of these models require coefficients that can only be obtained from full stress-strain test results that are not available in the testing database. Therefore, a Bilinear Isotropic Hardening model has been used to simulate the material plasticity, assuming no hardening is occurring (Tangent Modulus = zero).

3 Testing protocol

The testing protocol consists of cyclic loading applied to the steel damper, aiming to evaluate its capacity and response under lateral forces. Deformation-controlled was used in the testing since structures’ seismic performance depends on resulting deformations rather than forces (more ductility than force-controlled tests). Figure 4 shows the loading protocol followed to perform this test (personal preference to monitor the damper’s displacement).

![Fig. 4. Loading protocol (Deformation-controlled test).](image)

The loading is applied at one end of the damper (A, at the beam), while the other end was assigned fixed support (B, at the column), as illustrated in Figure 5.

![Fig. 5. Loading protocol (Deformation-controlled test).](image)
4 Theoretical background

The steel damper is analyzed using finite element software Ansys Workbench [6]. The damper was first modeled using AutoCAD [7] as surfaces and exported to Ansys, while the geometry was created using the export file. The main target is to get the damper’s hysteretic behavior, which will then be used to get the characteristics of the damper.

To get the desired output, a series of different analyses have been performed. The first is a linear static analysis where the damper is loaded with a small remote displacement (1 mm) to excite the model. The analysis results are then used in an Eigenvalue Buckling analysis (Linear Buckling analysis), in which the mode shapes of the excited damper are obtained. Finally, the desired mode shape is then exported to a nonlinear static analysis in which the cyclic loading is performed to the damper and the hysteretic behavior is generated as a function of the reaction force and deformation. The resulting hysteretic behavior is used to get all the damper properties such as plastic stiffness, damping ratio, effective stiffness, and dissipated energy.

The parameters were calculated for each cycle to observe properties degradation while the material is approaching the ultimate capacity. However, since the hysteretic behavior for both dampers has many cycles, the last cycle is chosen to calculate the properties of the steel damper.

The dissipated energy is an important parameter to know which describes the amount of energy dissipated before the failure of the damper, and it can be calculated by finding the area under the load-displacement curve. The following parameter is the damping ratio. Figure 6 shows the parameters used to calculate the damping ratio as stated in Eq. (1) [1].

\[ z = E_D / (4pE_{SO}) \]  

(1)

The effective stiffness is an important parameter as it provides the needed information for the load-carrying capacity of the damper. Other parameters like the elastic and plastic stiffnesses can be obtained from the hysteretic graph. The equation used to calculate the effective stiffness is shown below [8].

\[ K_{eff} = K_P + (Q/X_{max}) \]  

(2)

\( K_P \) is the plastic stiffness, the slope of the loading line, and \( Q \) and \( X_{max} \) represent the slope of the line connecting the origin point with the point of maximum displacement.

![Force vs Displacement Graph](image)

**Fig. 6.** Estimation of equivalent damping ratio [1].
5 Results and discussion

The results captured parameters such as total deformation, deformation in certain directions, strains, stresses, etc. The chosen parameters discussed in this paper are the equivalent stress and the total plastic strain. These parameters are selected since they determine where the failure occurs.

The analysis showed that the damper has maximum stress of 304.5 MPa (critical stress showed in red colour), at the diaphragm plate since it is the smallest thickness in the damper. The maximum plastic strain is also on the diaphragm plate and near the load application area with 0.35 mm/mm (red colour), and that confirms that this region is the first part to yield in the damper and that’s precisely where the failure is expected to occur (buckling). Figures 7 and 8 show the stress and plastic strain distribution on the damper, respectively.

![Stress distribution (Ansys workbench)](image1)

Fig. 7. Stress distribution (Ansys workbench).

![Plastic strain distribution (Ansys workbench)](image2)

Fig. 8. Plastic strain distribution (Ansys workbench).

To obtain the hysteretic response of the damper, a deformation control is assigned to the face of the damper where a remote displacement is applied, which gives the maximum deformation experienced by the elements. The same face is assigned a force reaction probe to measure the applied force in the load application direction. The hysteretic behavior is shown in Figure 9.
The dissipated energy is obtained by calculating the area of the polygon (area under the last loop). Also, the effective stiffness and the damping ratio for the last loop are calculated using Eq. (1) and Eq. (2). The results summary is shown in Table 2.

### Table 2. Results summary.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dissipated Energy (Joules)</td>
<td>1440</td>
</tr>
<tr>
<td>Plastic Stiffness (N/mm)</td>
<td>3750</td>
</tr>
<tr>
<td>Effective Stiffness (N/mm)</td>
<td>7750</td>
</tr>
<tr>
<td>Damping Ratio (%)</td>
<td>37</td>
</tr>
</tbody>
</table>

### 6 Conclusions

This research showed the finite element analysis of a steel damper, where the characteristics of the damper were obtained (energy dissipation capacity, damping ratio, and effective stiffness). The damper was tested using a nonlinear static structural simulation via Ansys Workbench, where cyclic loading is applied to the damper. A bilinear isotropic hardening model was used to simulate the material plasticity. The results showed the stress and the plastic strain distribution in the damper with concentration at the diaphragm plate. The hysteretic behavior is also obtained and used to calculate the dissipated strain energy. A more realistic approach is to use a multilinear kinematic hardening model, which provides more accurate results. Given the energy dissipation capabilities of the proposed
damper, it is expected to have many applications to the earthquake-resistant design of structures, especially steel frames.

References