PARAMETRIC STUDY ON BUTTERFLY-SHAPED SHEAR LINKS WITH VARIOUS GEOMETRIES

A. Farzampour1 and M. Eatherton2

ABSTRACT

Structural steel plates oriented to resist shear loading can be used as structural fuses in seismic force resisting systems. Inelastic deformation and damage would be concentrated in the structural fuses while the surrounding elements remain elastic. Some fuse plates have engineered cut-outs leaving flexural/shear links that exhibit controlled yielding and dissipate seismic energy. A promising type of link described in the literature is the butterfly-shaped link that better aligns bending strength along the link length with the shape of the applied moment diagram. In previous studies, it has been observed that these links are capable of substantial ductility and energy dissipation. However, the effect of varying butterfly geometric parameters on the location of plastic hinges, the accumulation of plastic strain, potential for fracture or buckling, and the amount of energy dissipation are in need of more investigation.

A parametric computational study is conducted to investigate the shear yielding, flexural yielding, and lateral torsional buckling limit states for butterfly-shaped links. After validating the accuracy of the finite element (FE) modeling approach against previous experiments, 96 computational models with different geometrical properties were constructed and analyzed. Initial imperfections were implemented in the shape of the first buckling mode and scaled to a magnitude equal to the link length divided by 250. The resulting critical moment, corresponding critical shear force, the accumulation of plastic strains through the length of links as well as the amount of energy dissipation are investigated.

The results indicate that as the shape of the butterfly-shaped links become straighter or narrower in the middle, accumulated plastic strain values increase. The significant effect of plate thickness on the buckling limit state is examined in this study. Results show that overstrength values for these links (peak force divided by yield force) is between 1.15-4.5, with straighter links producing larger overstrength. Finally, the flexural limit state was found to dissipate more energy than either the shear dominated limit state or the buckling limit state.

1 Graduate Student Researcher, Dept. of Civil Engineering, University of Virginia Tech, Blacksburg, VA 24060 (email: afarzam@vt.edu)
2 Associate Professor, Dept. of Civil Engineering, University of Virginia Tech, Blacksburg, VA 24060
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A. Farzampour and M. Eatherton

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Structural steel plates oriented to resist shear loading can be used as structural fuses in seismic force resisting systems. Inelastic deformation and damage would be concentrated in the structural fuses while the surrounding elements remain elastic. Some fuse plates have engineered cut-outs leaving flexural/shear links that exhibit controlled yielding and dissipate seismic energy. A promising type of link described in the literature is the butterfly-shaped link that better aligns bending strength along the link length with the shape of the applied moment diagram. In previous studies, it has been observed that these links are capable of substantial ductility and energy dissipation. However, the effect of varying butterfly geometric parameters on the location of plastic hinges, the accumulation of plastic strain, potential for fracture or buckling, and the amount of energy dissipation are in need of more investigation.

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Introduction

The ductile behavior of structures allows inelastic drift capacity and energy dissipation during severe earthquakes. Steel plates with shear links can be implemented to concentrate the inelastic deformation and damage in a specific structural element, and have the other surrounding steel members remain elastic. If these ductile members are also replaceable, they are sometimes referred to as structural fuses because they yield and thus limit the earthquake forces applied to the surrounding structure [1].

Several studies have indicated that steel plates having butterfly-shaped cutouts, as shown in Fig. 1, have advantages for use in structural fuses. Compared to other shapes of links (e.g. straight link also known as slit panels), butterfly-shaped links better align the moment capacity with the shape of the moment diagram leading to efficient implementation of the steel and more uniform yielding distribution along the length of the link. The planar geometry of the butterfly-shaped links make them applicable for space-constrained applications as well [2, 3].

1 Graduate Student Researcher, Dept. of Civil Engineering, University of Virginia Tech, Blacksburg, VA 24060 (email: afarzam@vt.edu)
2 Associate Professor, Dept. of Civil Engineering, University of Virginia Tech, Blacksburg, VA 24060
By utilizing structural fuses, the surrounding structure is protected from damage and significant inelastic deformations. The fuses are intended to be accessible and easily replaceable after an earthquake [2]. Butterfly-shaped metallic dampers (e.g. [3]) have been used as structural fuses in new structural beam application and joints to protect the beam-column connections from considerable damage during seismic loadings [4, 5]. The main feature of the fuse system is that the plastic deformation was concentrated at the butterfly-shaped dampers, while the beams and columns remain almost elastic. It is reported that the butterfly-shaped fuses are able to perform even under large shear angles of up to 30% across the link length [2] without losing strength. In addition, full hysteretic behavior under large story drifts is observed [4].

A number of studies have indicated that utilizing the slit, butterfly-shaped fuses or similar shapes can control the response of the multistory structure [4]. It is shown in laboratory test that the butterfly-shaped links are capable of having significant ductility and initial stiffness [2]. However, the possibility of brittle limit state occurrence (e.g. lateral torsional buckling), and low cycle fatigue [4] should be considered [1].

In this study, the effect of varying geometries on the location of the hinges, the accumulation of strains, the buckling limit state and the capability of dissipating energy are investigated. A Computational parametric study on 96 butterfly-shaped links with various geometrical properties is conducted to investigate the shear and flexural limit states as well as the buckling behavior of the different butterfly-shaped link geometries. The inelasticity concentration location, maximum strain values, overstrength factor and buckling effect on the load bearing capacity of the links are investigated for various geometrical properties.

**Parametric study description and example push-over curves**

The push over analysis is extracted from finite element analysis. ABAQUS software was used with explicit solver. First, the buckling analysis is done to extract the modal shapes of the butterfly-shaped links, and then push over analysis is conducted on a model including initial imperfections (Fig. 2). The initial imperfections are applied in the shape of the first buckling mode scaled to have maximum out-of-plane displacement value of L/250.

The modeling methodology and detailed plan for the different cases of the parametric study are determined as follows. Based on the previous studies [6, 7, 8], the reduced integration shell
element with four nodes is used to mesh links. The L value is set to be 0.5m. The L/t is chosen to have the values of 10-20-40-60-80-100 to study the effect of thickness and buckling limit state. The a/b values are 0.1, 0.33, 0.75, 1, and the b/L values are 0.1, 0.2, 0.3 and 0.4.

The boundary condition at the bottom is fully fixed, while the boundary condition displacements at the top is fixed for out-of-plane and vertical displacements simulating the laboratory experiment test setup (Fig. 2). The displacement loading is applied on the top edge of the tested butterfly-shaped link.

![Figure 2. General properties of a model in ABAQUS](image)

The material constitutive model is taken as the average values from the laboratory tests conducted on the shear links. The yielding stress of 273 MPa, and the ultimate stress of 380 MPa are used as constitutive model with the linear hardening of 1 percent of elastic modulus for post yielding material properties. The modeling methodology is verified against the laboratory test by Ma et al. (2011), Specimen B10-36, as shown in Fig. 3.

![Figure 3. Verification of finite element modeling methodology against Ma et al. (2011)](image)

Three limit states, flexural yielding, shear yielding and lateral torsional buckling were identified as the important limit states for butterfly shaped links. The pushover curves are extracted based on the summation of the forces at the bottom edge and recording the displacements at the top edge of the links. In general, links that do not buckle will experience a ductile limit state (e.g., flexure as shown in Fig. 4) and undergo geometric hardening until the next ductile limit state (e.g., shear as shown in Fig. 4). Geometric hardening occurs at large shear deformations as the links resist axial tension due to the boundary conditions.
At Point 1 in Fig. 4, the flexural limit state governs the yielding of the link as plastic hinges form at two locations along the link length. After some hardening, at Point 2, the shear limit state is observed at the middle of the link. Models that experience buckling (not shown here) experience loss of the load-carrying capacity. The variable $V_1$ is defined as the shear force associated with the first limit state, while $V_{\text{max}}$ is the maximum shear strength of the link.

Figure 4. General pushover for a typical butterfly-shaped link

At Point 2, the plastic strain is concentrated in the middle and the shear hinge at the midpoint length of butterfly-shaped. From this point, the whole link acts as mechanism and the strength and stiffness degrade significantly. After the second limit state, the butterfly-shaped link does not have capability to resist the load. A pushover curves that demonstrates the occurrence of shear limit state first is shown in Fig. 5. It is observed that the butterfly-shaped link has experienced shear limit state at Point 1. The geometric hardening then occurs due to axial elongation of the link. The flexure limit state occurs after this part and the link strength and stiffness degrades afterwards, which is observed at Point 2.

Figure 5. Pushover curve for shear dominated model

The third limit state, lateral torsional buckling, but is highly dependent on thickness of the
link. Some link configurations buckled before reaching either ductile limit state, or others achieved the first buckling limit state and then experienced strength degradation due to buckling. Fig. 6a shows a model with buckling due to the low thickness. Lateral torsional buckling of butterfly-shaped links is investigated in detail in Farzampour and Eatherton [3] and is discussed more in later sections of this paper. Fig. 6b shows the effect of thickness on load bearing capacity of the links, in which $V_{\text{pred}}$ is calculated based on the Eq. (1) or Eq. (2).

![Plastic strain](image)

### Figure 6. Pushover curves for the models with different thickness values

#### Investigation of the output parameters

Pushover curves were analyzed to monitor several parameters of interest. The plastic strain was extracted for each model at a specified drift ratio of 5 percent. The average distance of the elements with highest plastic strain values to the middle of the link are reported as the hinging location. It is observed that the hinge location is independent thickness values ($L/t$) since all six lines of each subplot are nearly identical in Fig. 7. Similarly, the width of the link ($b/L$) has little effect on hinge location. The hinge locations are shown to be near zero (shear limit state) for $a/b=0.1$, near 0.5 for $a/b=0.33$, and equal to 1.0 (flexural hinges at ends) for $a/b$ equal to 0.75 or
1.0. This is consistent with past research which derived a value of $a/b=1/3$ to concentrate inelasticity at the quarter points [2].

![Graphs showing hinge location from the middle of the butterfly-shaped link](image)

**Figure 7.** The hinge location from the middle of the butterfly-shaped link

The maximum equivalent plastic strain anywhere in the model is recorded at 5% drift ratio. The equivalent plastic strain value is relatively low for all the groups except for $a/b$ equal to 1 (shown in Fig. 8a), which validates the observation in previous literature that these links can prone to fracture, especially with thicker plates. This further indicates that the slits could be highly prone to fracture compared to corresponding butterfly-shaped links. It is shown that for a specific $a/b$ ratio, the $L/t$ values would not change the plastic strain results as much as $a/b$ ratio of the links (Fig. 8b).

![Graphs showing summary of plastic strain results](image)

**Figure 8.** The summary of plastic strain results

It is concluded that, for the shear-dominated models, the plastic strains are larger due to
geometrical discontinuity at the middle and larger deformation demands to get the same drift angle. Along the same lines, for the links with inelasticity far from discontinuities (e.g. for a/b=0.33), the plastic strain is lower since the inelasticity is concentrated far from the discontinuities at the middle and ends. \( V_{\text{max}} / V_1 \) is the maximum force extracted from the push over curves normalized to the first limit state. The overstrength curves shown in Fig. 9 are decreasing with increasing b/L ratio. It is shown that for a/b equal to 0.33 the overstrength ratio would be lower than the rest of the models, which would efficiently reduce the cost of the boundary elements for the design purposes.

![Graphs showing maximum force over first limit state extracted from push over analysis](image)

**Figure 9.** The maximum force over first limit state extracted from push over analysis

The normalized energy index is calculated as area under the push over curve divided by a rectangular area up to a displacement of 0.2m with a normalized force of 1. The energy index is affected by how thin the butterfly-shaped link is. If the plate is thin enough, it is more prone to buckling, and has less capacity to dissipate energy, which is observed in Fig. 10. For all of the butterfly-shaped links, an increase in b/L would decrease the energy dissipation capability, which means that the shear governed link would not be as effective as flexure governed link. In addition, the links are investigated under cyclic loading; however, the responses are not shown here.

It is observed that the links having thicker plates have significantly better performance compared to thinner links, which is confirmed with the monotonic study as well. Along the same lines, the shear-dominated links show better energy dissipation capability lower drifts values since the plastic strains are limit at the first stages of loading cycles.
The forces associated with flexure and shear limit states, based on the previously proposed equations are calculated for each model [3]. Based on the geometrical properties of each model, the forces associated with flexure and shear limit states are formulated in Eq. (1) and Eq. (2), respectively [3].

\[
V = \frac{a \sigma_y (2b - 2a)}{L} \quad \text{Flexure Limit state} \tag{1}
\]

\[
V = a t \left(\frac{\sigma_y}{\sqrt{3}}\right) \quad \text{Shear Limit state} \tag{2}
\]

In which \(\sigma_y\) is the yielding stress. All the variables’ definitions are shown in Fig. 1. The governing limit state, \(V_{\text{pred}}\), is calculated based on the minimum values of flexural and shear limit state. Shear limit state equation is a linear function of mid-width (shown as a); however, flexure limit state equation is a quadratic function of mid-width (a). Along the same lines, shear can control for larger b/L even if flexure controls for smaller b/L values which is observed in Fig. 11.
Shear forces associated with first limit state, $V_1$, obtained from FE models are divided by $V_{\text{pred}}$ in Fig. 12. This ratio is affected by how thin the butterfly-shaped link is. It is noted that for the thinner butterfly shaped links, the $V_1/V_{\text{pred}}$ is lower 1.0 due to the initiation of buckling. From the analysis, it is concluded that for the links with a/b ratio equal to 0.1 and 0.33, narrow links (lower b/L) would produce $V_1/V_{\text{pred}}$ less than 1. However, for the models with a/b ratio equal to 0.33 and 0.75, wider links (larger b/L) would produce smaller $V_1/V_{\text{pred}}$. This means that if the narrower links are used, the yielding capacity of the link would not be fully achieved.

In general, it is shown that narrow butterfly-shaped links would not be useful due to buckling issues and less energy dissipation, although other geometrical properties are important to be considered for buckling investigation purposes [3]. The average value of $V_1/V_{\text{pred}}$ for models with a/b equal to 0.1, 0.33, 0.75 and 1 are approximately 0.94, 0.95, 1.0, and 0.98 for L/t up to 40.
Conclusion

Parametric computational study is done to investigate the shear yielding, flexural yielding limit states, and lateral torsional buckling of butterfly-shaped links for 96 computational models. The resulting critical moment, corresponding critical shear force, the accumulation of plastic strains through the length of links as well as the ability of energy dissipation of different geometries are investigated.

The trends in observed plastic hinge location validate previously derived equations that suggest $a/b=0.33$ is a transition from hinging at the ends ($a/b>0.33$) to shear yielding at the middle ($a/b<0.33$). In addition, the plastic strain values are as much as five times higher for straight links ($a/b=1.0$) as compared to butterfly-shaped links with $a/b$ ratios of 0.33 and 0.75, which suggests higher potential for fracture which is observed in previous studies [9]. The significant effect of the plate thicknesses on buckling is observed, which also affects the energy dissipation; however, the location of the hinge formation is independent of thickness. It was found that the shear limit state dissipates less energy than the flexural limit state. In general, considering the plastic strain results, the $a/b$ ratio equal to 1/3 is recommended since the possibility of the fracture would be lower, inelasticity would concentrate far from the discontinuities and the overstrength is lower which is desirable for economical boundary element design.

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