Innovative Lateral Resisting Systems with Seismic Protective Dampers and Guideline Design Procedures

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Abstract
Several conventional structures are in need of proper design and construction to resist seismic loads without experiencing a significant amount of damages. Sufficient strength and stiffness of seismic protective devices would eventually reduce the structural vulnerabilities due to the serious damage under seismic loading. There are variations of structural elements with adequate ductility and energy dissipating capability, which could be implemented as structural fuses to reduce the seismic effects, especially for high-rise buildings. For this purpose, dampers are typically used for improving the seismic energy dissipation, the concentration of the damages in a specific part of the system, proving more ductility, and reducing the unpredictable high plastic strains within the structures. In this study, the widely used conventional eccentrically braced systems are considered for further investigations, and the effects of the implementation of the seismic links in multi-story structures are analyzed for multi-story prototype structures by using verified computational models. Subsequently, innovative seismic protective dampers consist of several butterfly-shaped shear links with a linearly varying width between larger ends, and a smaller middle section is introduced. Ultimately, guideline design procedures are developed for redesigning the conventional eccentrically braced frame (EBF) systems with innovative seismic protective dampers, and backbone curves are derived and compared accordingly.

Keywords: Lateral Resisting System, Damper, Shear link, Eccentrically braced frame

1. Introduction
Under severe earthquakes, the ductile behavior of the structural elements allows inelastic drifts leading to the overall system’s energy dissipation capability Farzampour and Eatherton (2019a), (2019b); Farzampour and Yekrangnia (2014); Luth et al. (2008), Paslar et al. (2020a); Mansosuri and Farzampour (2018). In various structural applications, shear links could be implemented by strategic material removal to concentrate the inelasticity and damages in one part of the structure while the remaining parts are intact and undamaged Farzampour (2021); Farzampour et al. (2018); Kim et al. (2016), Farzampour (2015); Paslar et al. (2020b). Along the same lines, a promising type of structural fuse for use in different structural applications is butterfly-shaped beams in which the steel web plate has cutouts inside leaving butterfly-shaped links for compatible aligning the capacity diagram with the corresponding demand diagram Castaldo et al. (2016); Lim and Kim (2017). Figure 1 shows the implementation and details of the butterfly-shaped beam in different structural applications. The reduction of plasticity concentration points at the critical sharp geometrical areas within the dampers had raised several issues previously. For this purpose, several new damper shapes including butterfly-shaped dampers are proposed recently to avoid significant concentrations of plasticity within a specific point Farzampour (2019); Farzampour and Eatherton (2019a), (2019b). This concept could be implemented as beam-column connection protection from significant damages under earthquakes for designing various high-rise and low-rise buildings as well as the fortification of the existing structures. In-plane implementation of the fuses has been shown to have substantial energy dissipation capability, ductility, and large distribution of yielding. To control the drift response of mid-rise buildings in-plane fuses have been implemented with similar shapes compared to butterfly-shaped fuses for the purposes of desirable energy dissipation and reducing the demands on the framing members Liu et al. (2015). These new dampers are able to concentrate the plastic deformations in structural shear links while the columns and beams remain almost elastic. In addition, several studies showed that these fuses are able to undergo 30% shear angle ratios if the possibility of buckling is prevented Farzampour and Eatherton (2019b); Keh-Chyuan et al. (1993); Esteghamati and Farzampour (2020). Figure 1b shows a typical butterfly-shaped shear link, and the general loading condition and geometrical properties, and the moment demand versus moment capacity of these links.
Along the same lines, different studies showed that straight shear links and butterfly-shaped shear links are capable of controlling the structural response of multistory buildings under earthquakes, and then be accessible for replacement purposes Farzampour (2019); Farzampour and Eatherton (2019b). These links represent high ductility and stiffness; however, they are subject to brittle limit states, especially buckling Farzampour (2019). The structural shear links employed in various applications
could act as structural fuses since they are able to yield and limit the demand forces on the surrounding structural elements. For addressing various limit state issues, the effect of various geometrical properties is studied previously to indicate appropriate design ranges for specific applications Farzampour and Eatherton (2018); Liu et al. (2015); Whittaker et al. (1991). It is shown that compared to other types of links, the butterfly-shaped links are capable of having hinges far from the sharper areas, full hysteric behavior, significant buckling resistance, and applicable for space-constrained areas.

2. Data preparation and reduced-order model establishment for analyzing the EBF structural systems with BF dampers

The modeling methodology with OpenSees is conducted by validating the cyclic behavior against the FE model. A butterfly-shaped beam is established following the typical conventional EBF system recommended by IBC IBC (2012) code provisions and redesigned with a set of flexural dominated links based on the guidelines provided in this study with a total beam length of 120 cm following previous studies Farzampour (2019). The geometrical properties of the model are shown in Figure 2, the material model is based on the yielding stress of 250 MPa, modulus of elasticity of 2.0E+5 MPa, and the strain-hardening ratio of 0.0005.

For verifying the reduced-order model with the FE model, a cyclic load previously proposed by AISC 341-16 for EBF behavior investigations is applied at one end of the shown beam in Figure 2, while the other end was fixed. This loading protocol is chosen due to having similarity in behavior of the EBF system with the studied butterfly-shaped beam. The studied FE model is shown in Figure 2 with geometrical details.

Figure 2 shows the schematic illustration of the Opensees reduced-order model. For this model, the beams are modeled with element elastic elements, since the contribution of the upper and lower plates to the inelastic total inelastic behavior is negligible. The butterfly-shaped links are established with a displacement-based beam element (dispBeamColumn) with distributed plasticity and 5 integration points. The length of the beam is equal to 120 cm, and the height of the beam is equal to 40 cm. The Isotropic Strain Hardening material, Giuffré-Menegotto-Pinto, is considered with a yielding point of 248 MPa, modulus of elasticity of 2e5 MPa, and strain-hardening ratio is 0.0005.

For verifying the reduced-order models with FEA. The hysteretic results of the reduced-order model verification study show that the reduced-order model is able to capture the cyclic behavior of a typical butterfly-shaped beam with more than 98% accuracy.

In this paper, the detailed guideline on the behavior of the recently suggested dampers is developed for use in designing various structural applications. The limit states governing the ductile and brittle behavior are determined and the stiffness tuneability is discussed in detail. Subsequently, FEM models the results of the developed models are culminated in deriving force-displacement behavior for a typical butterfly-shaped beam and compared with conventional linking beam, and details are explained with aid of the developed guidelines.

Figure 1. Butterfly-shaped link and applications (a) implementation of a butterfly-shaped fuse in various applications, (b) the geometrical shapes, and the loading condition of a typical butterfly-shaped link.

Figure 2. The schematic representation of the FBF model in OpenSees.
3. Design of multi-story structure with structural shear links based on the design guidelines and comparisons of the behavior

To investigate the effects and applicability of the butterfly-shaped shear links on structures, the example for the EBF system from SEAOC IBC (2012) is considered. After designing the new multistory structure with butterfly-shaped shear links, both systems are computationally modeled with aid of Openseees software. In addition to satisfying the equilibrium, and considering Figure 3, the following equations, Eq. (1) and Eq. (2) are derived for obtaining the force, related to the butterfly-shaped link. Eq. (1) could be derived from the general equilibrium condition of the horizontal beam at the top of the butterfly-shaped damper, and the Eq. (2) is derived based on the total equilibrium of the system.

\[ V_{BF} = \frac{2M}{H} \quad \text{and} \quad M \\
= \frac{VL}{2} \]

\[ 2M - VL + HV_{BF} - V_{BF}H = 0 \]  \( (2) \)

Therefore, Eq. (3) could be derived based on the simplification of the previous equations.

\[ V_{BF} = \frac{V \times H}{L} \]  \( (3) \)

The flanges of the beams are designed based on the mentioned sectional properties determined in SEAOC IBC (2012). In each story, the links with strategic cutout are implemented as the connecting beam. The fuses design is based on the guidelines provided in previous sections, and the demand force for each story level. It is noted that the learning columns are considered within this study to have a P-delta effect. The gravity force is calculated based on the seismic weight associated with each story and divided by two, to have the gravity load associated with leaning columns for each lateral resistance EBF system. The damping is applied based on the Raleigh method for the periods associated with the first and second modes.

The damping ratio is considered to be 0.02 for which a and b terms associated with the Raleigh method are calculated and implemented within the models. It is noted that the conventional EBF system is designed in such a way that the linking element is yielded in shear. The EBF system is designed with the aid of the zero-length element since the shear is governed according to SEAOC IBC (2012). The zero-length elements are used for y-direction between the link beam and the point in which the brace and beam are intersected. The purpose of a zero-length element is to simulate the shear stiffness of a system; therefore, it yields when the vertical demand reaches a specified force. The new models with butterfly-shaped shear dampers displacement-based beam element (dispBeamColumn) are considered to simulate the effects of the damper under the same designed forces.

4. Conclusions

The strategically shifting toward the ductile mechanism from buckling and yielding in tension toward local flexure and shear yielding would enhance the hysteretic behavior and energy dissipation. In this study, the widely used conventional eccentrically braced systems are considered for further investigations, and the effects of the implementation of the seismic links in multi-story structures are analyzed for multi-story prototype structures by using verified computational models. Subsequently, innovative seismic protective dampers consisting of several innovative shear links with a linearly varying width between larger ends and a smaller middle section are introduced. For this purpose, guideline design procedures are established for redesigning the conventional EBF systems with innovative seismic protective dampers, and backbone curves are derived and compared accordingly.

4. References


