Multi-Story Buildings Equipped with Innovative Structural Seismic Shear Fuse Systems

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Abstract: Infrastructures could be designed and constructed to resist seismic lateral loads without experiencing a significant amount of damage concentrations in specific area. Having sufficient strength and stiffness to reduce the structural vulnerabilities against serious damages under seismic loading, requires structural elements to have adequate ductility and energy dissipating capability, which could be provided with the use structural dampers. These elements are typically replaceable, and designed to yield and protect the surrounding members from damages, and then be accessible after a major event.

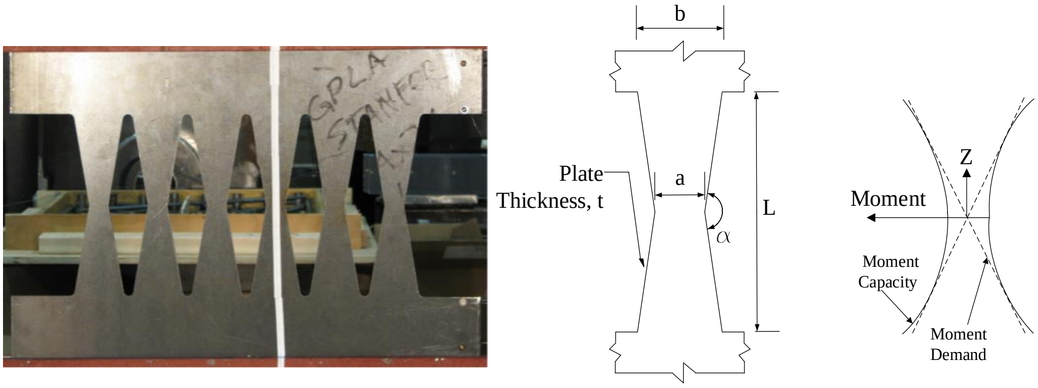
In this study, butterfly-shaped links with linearly varying width between larger ends and a smaller middle section are used for redesigning the prototype structures due to substantial ductility and stable energy dissipation capability. The effect of implementation of innovative seismic dampers in multi-story structures is investigated by analyzing multi-story prototype structures with structural seismic shear dampers, and subsequently compared with simple conventional linking beams. The results of the nonlinear response history analysis are summarized for 44 ground motions under maximum considered earthquake (MCE) and designed based earthquake (DBE) hazard levels. It is shown that implementation of the butterfly-shaped dampers in buildings with similar stiffness and strength leads to higher dissipated energy and less pinched curves compared to typical eccentrically braced frame systems. It is determined that the general stiffness and strength of the system with the butterfly-shaped link is close to conventional models; however, the demands on the surrounding boundary elements are lower than the corresponding conventional model, which could be beneficent for improving the seismic performance of the structural systems.

Keywords: Structural shear dampers, Hysteretic damper, Non-linear response history analysis, Eccentrically braced system

1. Introduction

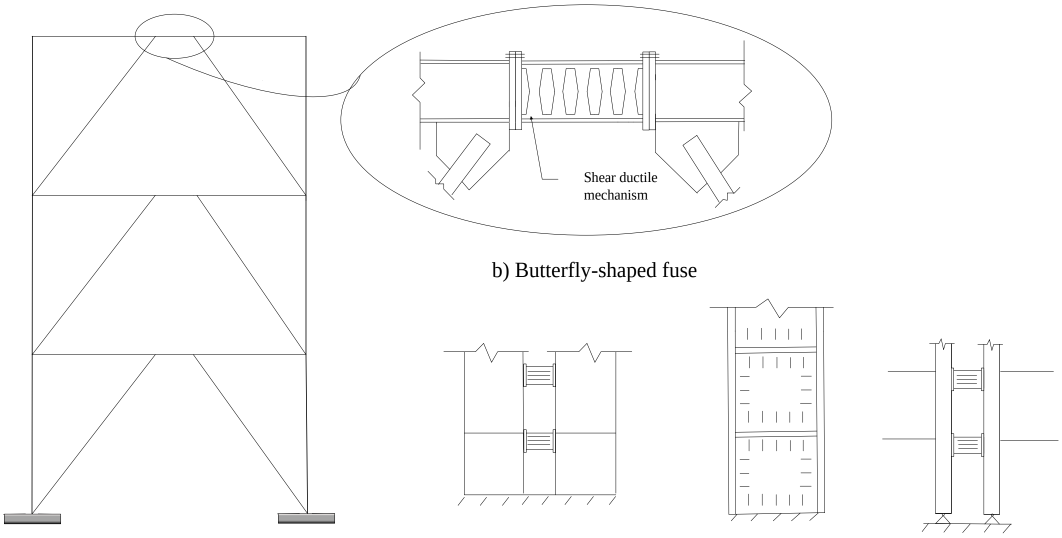
Infrastructures could be designed and constructed to resist seismic lateral loads without experiencing a significant amount of damage concentrations in specific area. Having sufficient strength and stiffness to reduce the structural vulnerabilities against serious damages under seismic loading, requires structural elements to have adequate ductility and energy dissipating capability, which could be provided with the use structural dampers. These elements are typically replaceable and designed to yield and protect the surrounding members from damages, and then be accessible after a major event. To limit occurred damages to multi-story buildings under severe earthquakes; shear dampers are implemented to allow inelastic displacements with sufficient energy dissipation capabilities. Shear dampers in general are used as sacrificial structural elements to protect the surrounding members from inelasticity accumulations, while concentrating the damages in a specific area by using the ductile features of the steel material. To adequately develop ductility and energy dissipation capability in structures, steel plates with strategic cutouts are implemented for which the ductile limit states are considered for design purposes under shear loading (Kobori 2017; Martinez Rueda 2002; Whittaker et al. 1991; Kobori et al. 1992; Farzampour 2022, Farzampour et al. 2015, Farzampour et al. 2020; Kim et al. 2022).

One class of typical dampers used in building for seismic energy dissipation and lateral force resistance consists of steel plate with cutouts leaving butterfly-shaped shear dampers (BF). Figure 1 shows steel plates with butterfly-shaped shear dampers inside for seismic resistance and inelasticity concentrations. The controlled yielding limit states far from the sharper areas over brittle limit states (e.g. buckling) made butterfly-shaped dampers appropriate for use in structural applications. Several applications of these damper system are shown schematically in Figure 2. Butterfly-shaped dampers are able to better align the capacity strength with demand diagram to have full hysteretic behavior and higher ductility. From Figure 1. b and Figure 1. c, it is concluded that the shape of the demand diagram varies linearly along the length of the dampers, while the strength diagram varies with quadratic format meaning that by selection of appropriate geometrical adjustments, the location of the yielding under flexural stress could be controlled, and yielding stresses are developed uniformly between the two ends of the structural shear dampers. New paragraph: use this style when you need to begin a new paragraph.



a) Butterfly-shaped plate (from Ma et al. 2011)		b) Geometry		c) Moment diagram

Figure 1. The butterfly-shaped hysteretic damper and details



b) Butterfly-shaped fuse

a) Eccentrically Braced Frame Application

c) Coupled shear wall Application

d) Shear wall Application

e) Linked column Application

Figure 2. Applications of the buttrefly-shaped dampers in structural systems

Several studies on steel plates with butterfly-shaped cutouts are conducted to show that these seismic structural dampers have advantages for use in structural systems. It is reported that butterfly-shapes dampers are able to efficiently use the material, and have more uniform distribution of stresses over the length of the damper. These dampers if appropriately designed are able to have full hysteric behavior even in higher drift ratios compared with conventionally implemented straight dampers. In addition, the resistance against buckling and controlled flexural yielding limit state occurring at quarter points are among the useful features of these links (Martinez Rueda 2002, Farzampour et al. 2018, Farzampour et al. 2019, Farzampour et al. 2021, Dehghani et al 2019,). The planar geometry of butterfly shaped links and considerable energy dissipation capability makes these dampers suitable for use space-constrained buildings (Ma et al. 2011).

The structural shear dampers are typically designed to be replaceable after earthquakes. These elements are constructed to be reachable and accessible for further repair and replacement (Kobori 2017). Several studies incorporated the butterfly-shaped shear damper or similar shapes for increasing the total dissipated energy of the whole system (Ma et al. 2011; Luth et al., 2008). Along the same lines, the structural shear links are incorporated in various applications; in steel plate shear walls for localizing the yielding and preventing the buckling (Hitaka and Matsui 2006); in beam-column connection areas to effectively protect the beam from concentration of inelasticity under large drifts (Oh et al 2009); in web of the beams to promote flexural yielding limit state as the major limit state specifically under seismic loading conditions (Aschheim and Halterman 2002 ; Shin et al. 2017); in mid-height building to prevent the surrounding members from damages and plastic strains (Esteghamati and Farzampour, 2020); and in self-cantering systems to increase the energy dissipation capability (Luth et al. 2008).

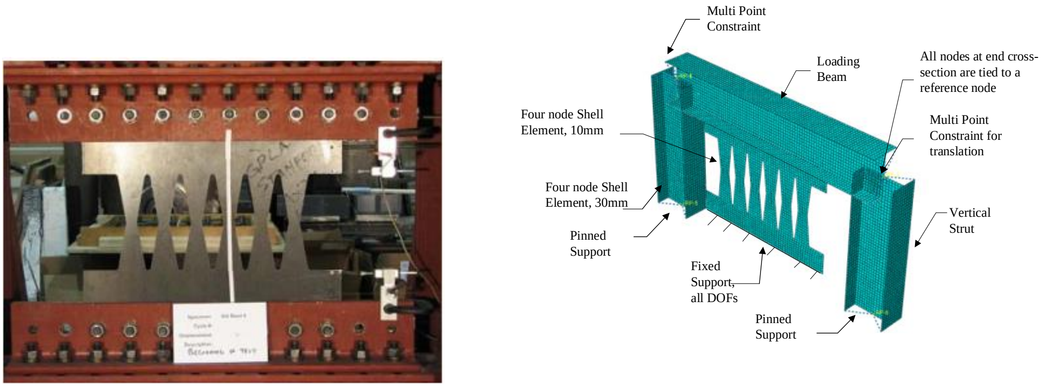
The strategically shifting the ductile mechanism from buckling and yielding in tension toward local flexure and shear yielding would enhance the hysteric energy dissipation of the structural system. In this study, the effect of structural links on different prototype buildings are investigated and compared with conventional structural systems. Along the same lines, new conFigureurations and design concepts converting global shear deformations into local flexural yielding mechanisms, which would be beneficial for steel structures applications due to improving the energy dissipation capability and reducing the demand on the structural boundary elements, are investigated. It is shown that by controlling the yielding mechanisms to occur as the flexure and shear across the discrete segments of the steel elements, the prototype buildings exhibit more desirable performance and efficient resistance against brittle limit states.

2. Verification of modeling methodology

To verify laboratory test conducted by Ma et al. (2011), the specimen B10-36W is computationally modeled due to having both limit states of yielding and lateral torsional buckling behavior at different drift intervals under cyclic loading conditions.

The test specimen is shown in Figure 3. a, and the computational model with details of boundary conditions is represented in Figure 3. b for which the bottom edge of the butterfly-shaped dampers are fixed and the upper edge is tied to a reaction frame in all degrees of freedom except horizontal displacement. Displacement control loading is applied on the edge of the reaction frame according to AISC loading protocol for eccentrically braced systems and following the test loading conditions. Four nodded reduced integration shell elements (S4R) with five integration points through the thickness of element are used for modelling purposes fore which the possibilities of the shear locking and hour glassing are avoided.

To obtain the hysteric pushover behavior, the dynamic explicit solver is implemented for monotonic and cyclic behavior. The material constitutive model is considered based on the reported coupon test results by Ma et al. (2011) in which the yield stress was 273 MPa, and ultimate stress was 380 MPa based on the coupon test results. The monotonic and hysteretic responses are captured with more than 95% in loading and 85% in unloading regimes compared to corresponding experimental results as it is shown in Figure 4.



a) B10-36W test specimen

b) Computational model developed in FE package

Figure 3. Finite Element Modeling methodology for verification purposes

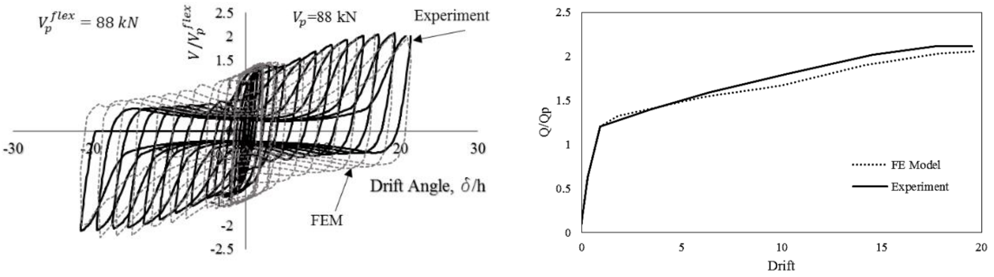
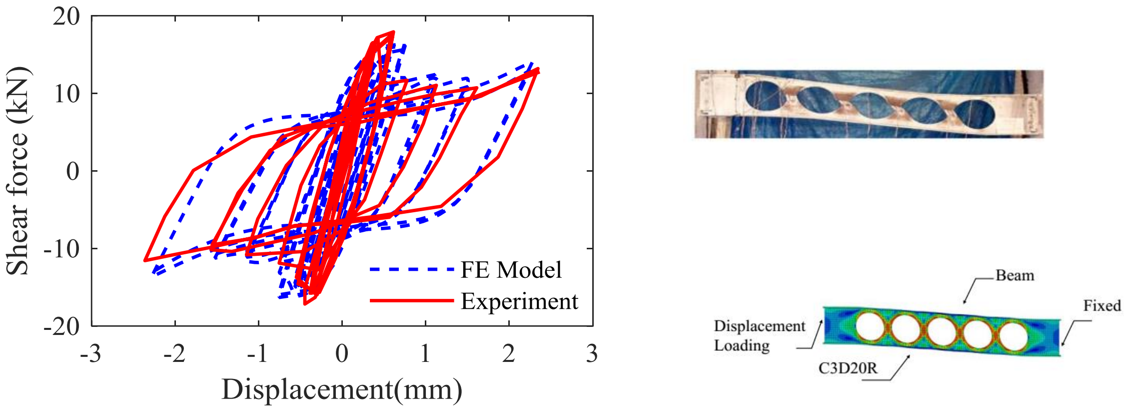


Figure 4. Verification of modeling methodology under cyclic AISC based on the loading protocols

2.2. Finite element modeling methodology verification with laboratory test II

The finite element modeling methodology is verified for a beam laboratory test equipped with hourglass shaped shear damper investigated by Aschheim and Halterman (2017). A detailed finite element model of the structural fuse is developed in FE package, and verified against experimental results studied. The experimental study consists of an interior beam with five circular cut-outs with the top and the base beams made of TS14×10×5/8 and TS16×12×5/8, respectively. The beam is then modeled using solid elements with controlled hourglass and shear locking effect (referred to as C3D20R element in ABAQUS) to obtain the second-order behavior with high precision.

Steel material is defined using a bi-linear stress-strain constitutive model with the yielding strength of 379 MPa, a strain-hardening modulus of 1.38 GPa, and an elastic modulus of 200 GPa. An initial imperfection of 1/250 of the beam’s length is considered to simulate the first mode of buckling. Subsequently, cyclic analysis is performed based on the ATC 24 loading protocol and cyclic pushover analysis is derived accordingly which is shown and compared in Figure 5. It is noted that the story shear force and drift of the FE model are taken as 1.43 and 0.75 times of the beam shear and chord rotation based on experimental setting geometry, respectively. It is shown that the considered numerical model has less than 5% discrepancies compared to the experimental results. In addition, the strength before and after buckling of the experimented beam, which is considered as the mode of behavior, are 76 kN and 57.4 kN, while the FE model captured the limits state behavior and the same strengths at the similar drift ratios with 73.2 kN and 52.7 kN, respectively.



a) comparison of cyclic pushover of butterfly-shaped shear fuse with experimental results

b) The FE modeling methodology

Figure 5. Verification of the proposed butterfly-shaped damper modeling methodology

2.3. Validation of reduced order models implemented for multi-story structures modeling and conventional systems

To validate the modeling methodology, a detailed steel plate with flexural dominated butterfly-shaped links (Farzampour 2021) is considered for redesigning the conventional prototype system (SEAOC 2012). The model length is 120 cm, and it was redesigned with ten butterfly-shaped dampers in a row. The height of the links is equal to 30cm, the mid-width length is equal to 3.8cm, the end width length is equal to 12cm, and the total height of the beam is equal to 40cm. The schematic representation of the model in FE package software, and the reduced order model in Opensees are shown in Figure 6 and Figure 7, respectively. The design shear according to SEAOC (2012) is taken to be 530 kN (120 kips) for which the material model is based on the yielding stress of 250 MPa (36 Ksi), modulus of elasticity is considered to be 2e5 MPa (29000 Ksi), and the strain-hardening ratio is 0.0005.

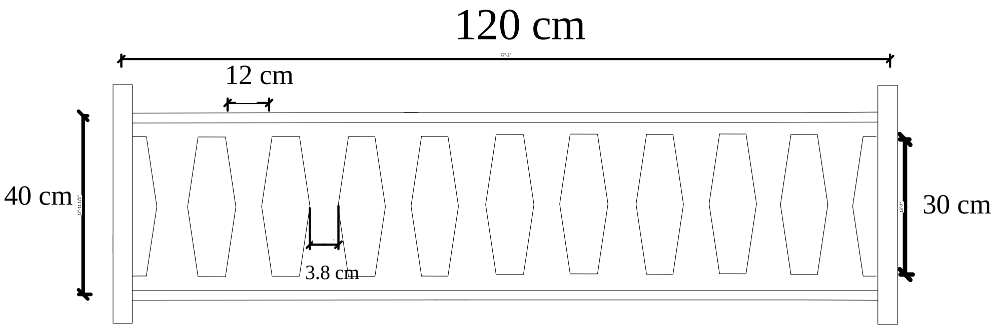


Figure 6. The schematic representation of the FBF model (the details are given in the text)

Figure 7 shows the schematic illustration of the reduced order model. For this model, the beams are developed with element elastic elements, and it is shown that the contribution of the upper and lower plates to the inelastic total inelastic behavior is negligible according to FE analysis. The butterfly-shaped links are modeled with displacement based beam element (dispBeamColumn) with distributed plasticity and five integration points. The length of the beam is equal to 120 cm, and height of the beam is equal to 40 cm to simulate the EBF prototype systems geometrical conditions. The end width, middle width and length of butterfly-shaped links are 12cm, 3.8 cm and 30cm. The links are modeled with taper shaped with varying width shown in Figure 7. The material model is Giuffré-Menegotto-Pinto Model with Isotropic Strain Hardening (Steel02 in Opensees) with yielding point of 36 Ksi (248 MPa), modulus of elasticity of 29000 Ksi (2e5 MPa) and the strain-hardening ratio is 0.0005 (CR1, CR2, a1, a2, a3, a4, and sigInt are 0.925, 0.15, 0.005, 1.0, 0.005, 1.0 and 0, respectively).

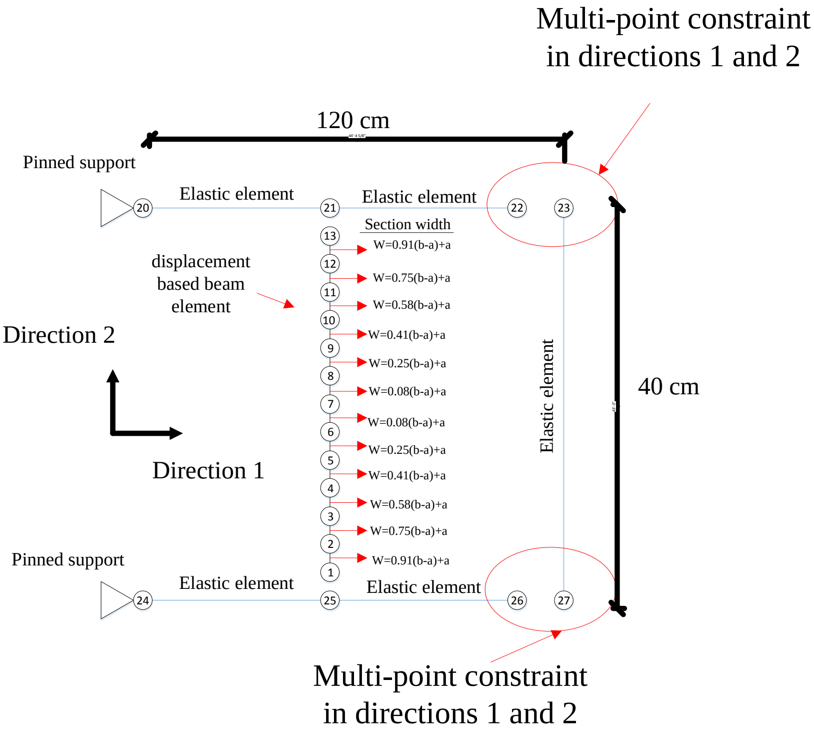


Figure 7. The schematic representation of the FBF model in Opensees

The modelling methodology with Opensees is conducted through validating the cyclic behavior against the model with similar geometrical and material conditions constructed in ABAQUS. For this purpose, a cyclic load suitable for EBF systems based on the general loading sequence protocol proposed by AISC is implemented. This protocol is used for link-column connections in EBF systems (AISC 2005). The loading protocol is based on AISC loading protocol and indicated in Table 1, and the comparisons of the hysteric cyclic response of the FE analysis with reduced order model analysis are summarized in Figure 8. The results show more than a 98% match between the two curves in both peak strength points in loading and peak strength points in unloading parts. In addition, from the FE model, it is observed that the flanges of the model remain almost elastic under the applied cyclic loading.

Table 1. The loading protocol (AISC 2005)

Cycle #	*Number of Cycles*	*Drift (%)*
1 to 6	6	0.0625
7 to 12	6	0.125
13 to 18	6	0.25
19 to24	6	0.375
25 to 30	6	0.5
31 to 36	6	0.75
37 to 42	6	1
43 to 46	4	1.5
47 to 50	4	20
51 to 52	2	3
53	1	5
54	1	6
55	1	7
56	1	9
57	1	11
58	1	13
59	1	15
60	1	17
61	1	19
62	1	21
63	1	23
64	1	25
65	1	27
66	1	29

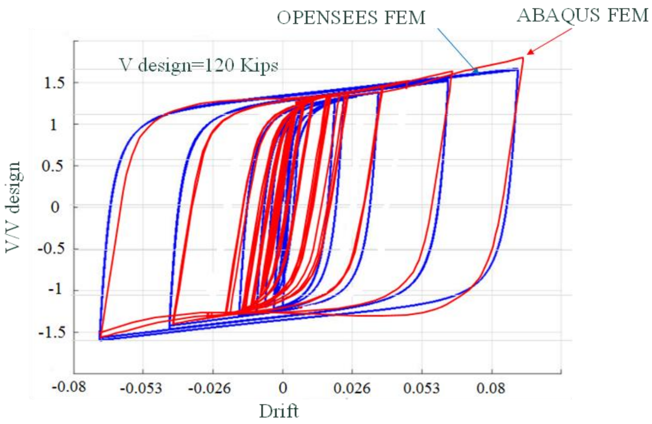


Figure 8. The verification of modeling methodology for reduced order models (120Kips is equal to 530 KN)

3. Dampers equipped with butterfly-shaped links design procedure

This design metrology is proposed to delineate the procedures to design damper equipped with butterfly-shaped shear links for multi-story buildings used in various seismic structural fuses. This section summarizes and elaborates the previous studies investigations on the shear, flexural and lateral torsional limit states of the links and lateral resisting system's design procedures (Farzampour and Eatherton 2017, 2081a, 2018b, 2019).

3.1. Limit states for dampers equipped with butterfly-shaped shear links

Energy investigations for structural shear links indicated that the capability of energy dissipation for the mentioned shear links having flexural limit state as the governing ductile mode of behavior could be significant (Farzampour, 2021). Desirable capability in dissipating the energy is related to inelasticity concentration location which is recommended to be far from the discontinuity area and geometrical sharp geometries (Ma et al, 2011). The design procedures mentioned in this section are an iterative procedure in which the geometry would be updated to avoid the brittle modes to be occurred.

In general, the flexure limit state is preferred over the shear limit state (Ma et al, 2011) due to two reasons. First, the inelasticity location could be far from the discontinuity areas, which reduces the chance of having fracture. Next, the energy dissipation studies show that the capability of flexural dominated butterfly shaped links in dissipating the energy for a specific amount of steel is higher than shear dominated ones (Farzmapour et al 2019). However, in several cases, it is not possible to have the flexural dominated links due to the space limitations or geometrical constrains; therefore, the shear limit state could be considered for design purposes instead.

The transitional equation for having the first yielding and ultimate capacity in flexure is estimated by what follows:

For a<b/2:

For the purpose of having flexure mode over the shear mode and based on Figure 1, it is required that the geometry satisfies the following Eq. (1) based on the previous studies (Farzmapour 2021):

(b-a)/L<0.28 (or α>148^0) Flexure dominated (1)

The shear and flexure capacity limit states are assessed as determined in Eq. (2) and Eq. (3):

$$P_p^{flexure} = \frac{2n(b-a)at\sigma_y}{L} \tag{2}$$

$$P_p^{shear} = n\frac{\sigma_y at}{\sqrt{3}} \tag{3}$$

For *a>b/2* or straight damper (*a=b*):

$$P_p^{flexure} = \frac{nb^2t}{2L}\sigma_y \tag{4}$$

$$P_p^{shear} = n\frac{\sigma_y bt}{\sqrt{3}} \tag{5}$$

In order to avoid buckling, and have flexure or shear ductile mechanism should be occurred before the brittle mechanism. Eq. (6) shows the minimum ductile strength based on the geometry of the link and Eq. (7) determines the lateral torsional buckling brittle limit state based (Frazampour and Eatherton 2019).

$$P^p = \min\left\{P_p^{flexure}, P_p^{shear}\right\} \tag{6}$$

$$P_{cr}^{LTB} = \frac{2\,E[0.533 + 0.547(a/b) - 0.281(a/b)^2 + 0.096(a/b)^3]bt^3}{L^2\sqrt{1+v}} \qquad (7)$$

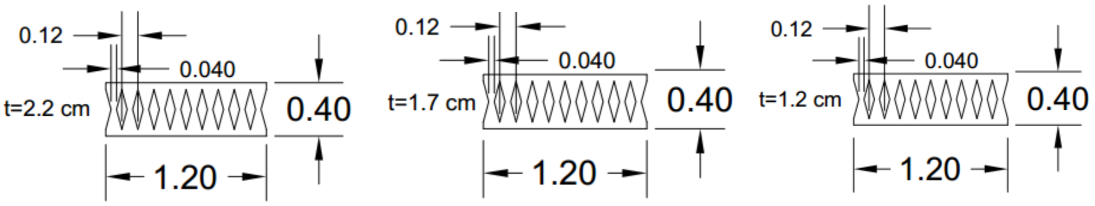
4. *Design of prototype six-story structure with structural shear links*

To investigate the effects and applicability of the butterfly-shaped shear links for conventional structures, the EBF system elaborated in SEAOC (2012) is considered and redesigned. Subsequently, both new system equipped with butterfly-shaped dampers and conventional system are computationally modeled with aid of Opensees package. Table 2 shows the demand forces on the shear links based on the SEAOC (2012) prototype EBF system.

Table 2. The shear for which the building is designed

Level	Shear (kips)	Cumulative Force (kips)	Design force for the BF links (kips)		Design groups
Roof	60	60	244	244	III
6th	60	120	244		
5th	88	208	358	358	II
4th	125	333	508	508	I
3rd	125	458	508		
2nd	125	583	508		

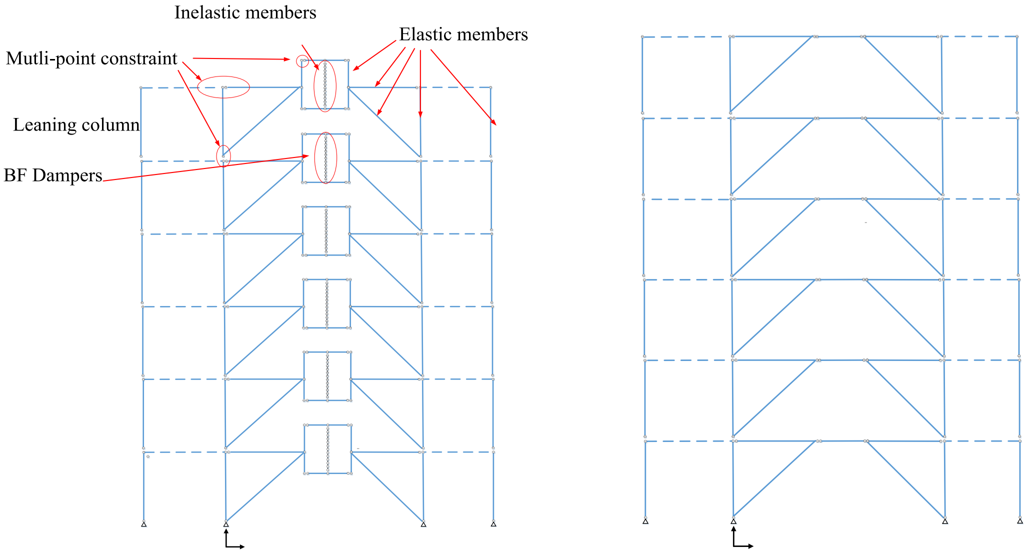
The three design groups are categorized as shown in Figure 9. Based on the previously provided equations (Farzampour, 2020), the links are designed to resist the demand forces reported by SEAOC (2012).



(I) (II) (II)

Figure 9. The schematic shapes of butterfly shaped dampers

The flanges of the beams are designed based on the mentioned sectional properties shown in Figure 9. In each story, the links with strategic cutout are implemented as the connecting beam. The six-story model with butterfly-shaped shear links is shown in Figure 10.a. In addition, the conventional model is developed to compare the new structural system with the corresponding EBF system, which is shown in Figure 10.b. It is noted that the leaning columns are considered within this study to incorporate the P-delta effect. The gravity force is calculated based on the seismic weight associated with each story to determine 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 first and second modes. The damping ratio is conisdred to be 0.02 for which a and b terms asscoiated with Raleigh method accoridngly.



a) The reduced order model with butterfly-shaped damper b) The reduced order model for conventional EBF

Figure 10. The computational models considered for nonlinear history analysis

4.1. The comparison of the monotonically loaded butterfly-shaped damper system with conventional EBF system

The pushover analysis is conducted by applying displacement controlled loading monotonically on the two models. The pushover of the two systems shown in Figure 11 indicates that both of the systems have similar initial stiffness, total mass and yielding regime. It is noted that for all the stories of the two models, the allowable drift ratio is confirmed based on the design forces, and none of drift ratios will pass 0.02 drift ratio limit as it is shown in Figure 12. Comparison of the building equipped with BF damper and EBF systems show that both systems start to yield at the similar strength level at all the story levels (Figure 13).

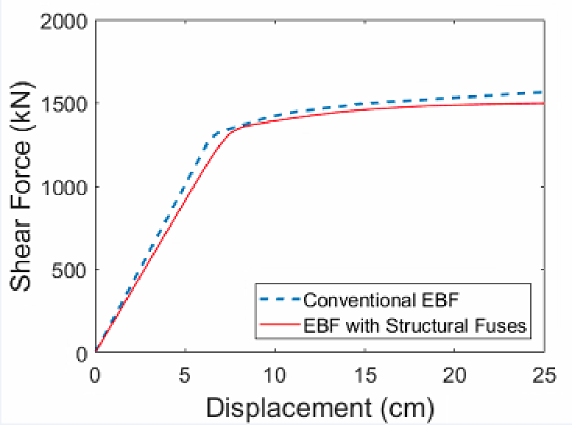
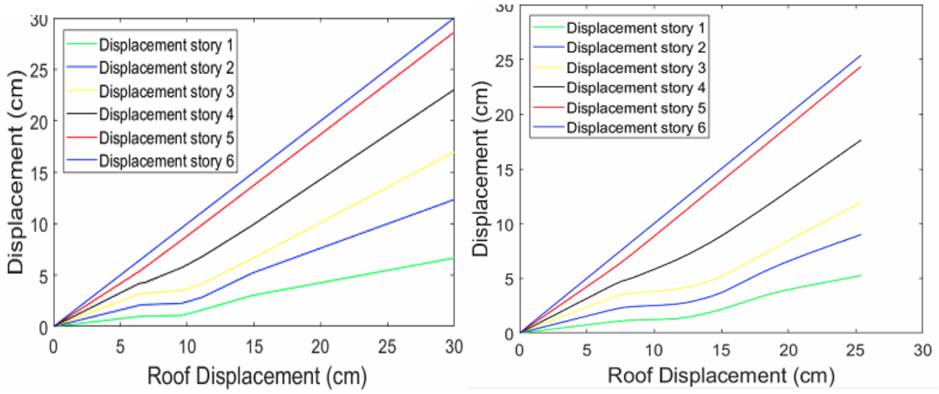


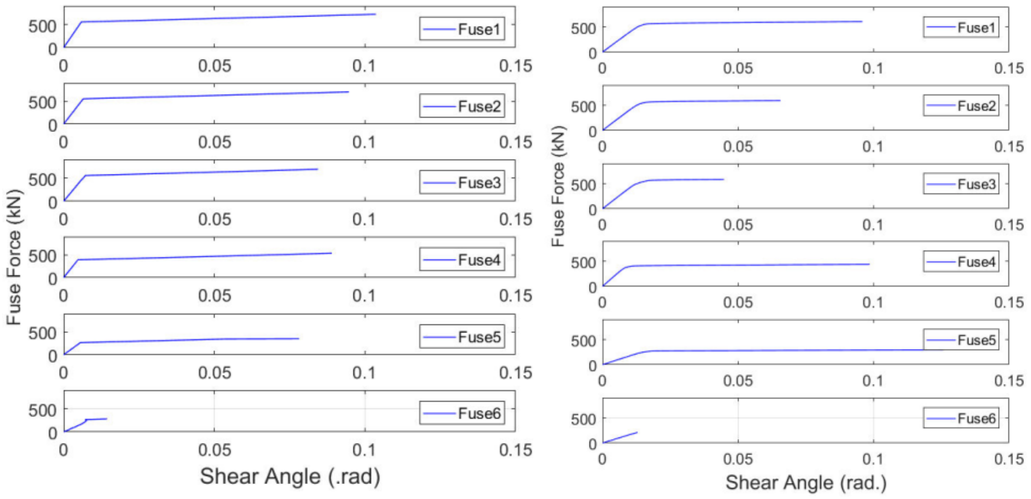
Figure 11. Pushover curves comparison for conventional system and the system equipped with BF dampers



a) Six stories with EBF system

b) Six stories with BF dampers

Figure 12. Comparison of story displacements



a) The EBF conventioanl system linking beam resposne behavior

b) The linking beam resposne for the system equipped with BF damper

Figure 13. The damper resposne under the monotonoc loading for six stories building system

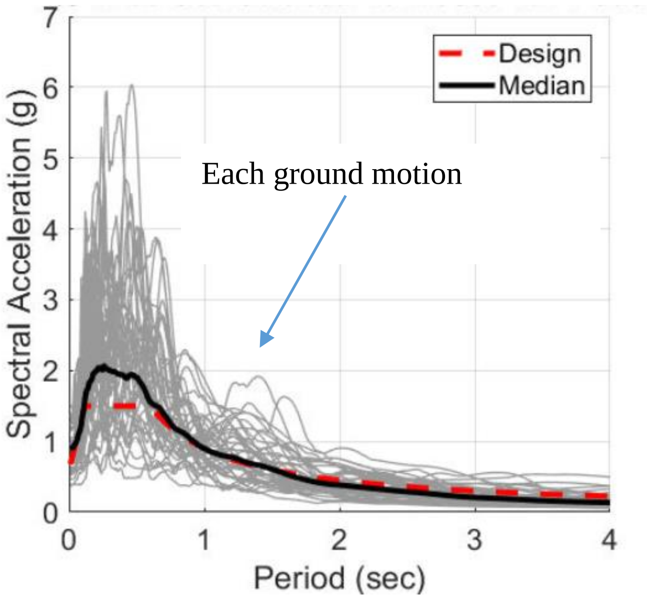
In addition, the Eigenvalues analysis is summarized in Table 3, which shows that for both of the systems, the natural frequencies are close. It is concluded that the stiffness of the two systems and the seismic mass is similar which estimated from the seismic weight associated with each story.

Table 3. Eigenvalues comparison of the conventional EBF system with the system equipped with BF dampers

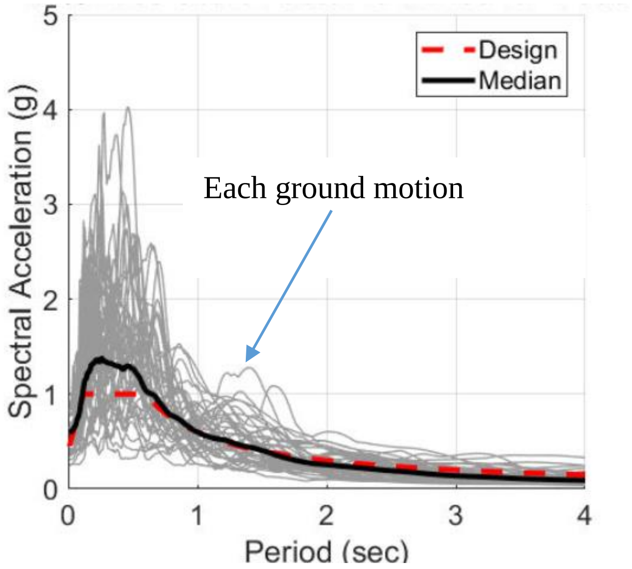
MODE NO.	**BF FUSE SYSTEM**	**CONVENTIONAL SYSTEM**
1	1.332	1.283
2	0.518	0.482
3	0.299	0.289
4	0.243	0.227
5	0.192	0.180

5. Discussion of the results for Nonlinear Response History Analysis (NRHA) for multi-story building:

Forty-four ground motions are considered for conducting the scale factor analysis. The ground motions are considered for two levels of Maximum Considered Event (MCE) and Design-Basis earthquake (DBE). The average of the 44 grounds motions spectrums is calculated and shown with a black line in Figure 14, and the design spectrum is illustrated with a red line based on the seismic provisions of AISC 341. The studied systems in general have a period of more than one second, depending on the system stiffness and system mass. The scale factor for a period equal to one second is calculated based on the design spectrum and 44 ground motions' average spectrum.



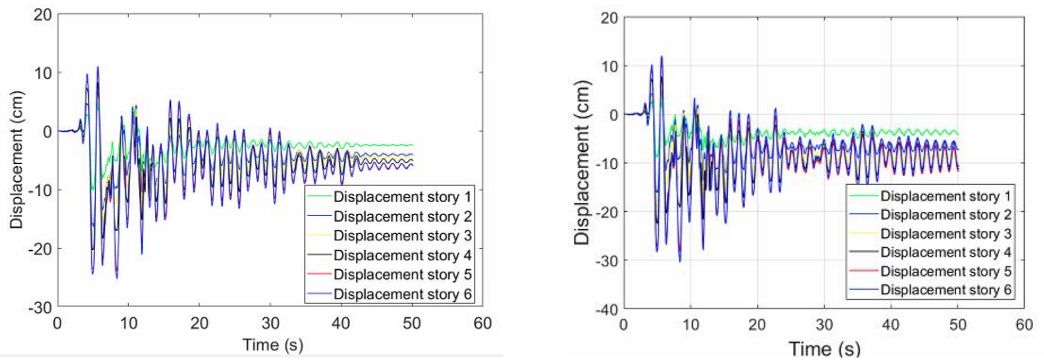
a) MCE level scale factor analysis, 2% in 50 scale factor



b) DBE level scale factor analysis, 10% in 50 scale factor

Figure 14. The scale factor assessment for two earthquake levels

The behavior of the designed frames under a specific ground motion shown in Figure 15 are investigated. Due to a slight difference in initial stiffness of the EBF system with BF damper equipped system, the story displacements for six-story frames with BF dampers are slightly higher than the corresponding conventional EBF system, which is shown in Figure 15.

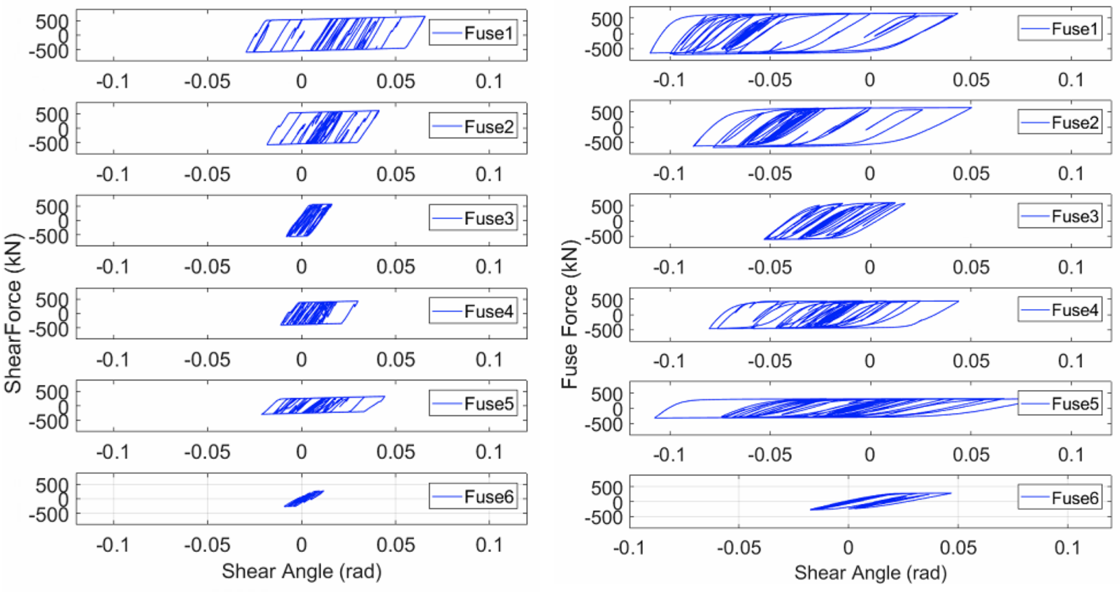


a) displacement time history analysis for BF fuses

b) displacement time history analysis for EBF system

Figure 15. Story displacement comparison of the two systems under earthquake loading

The energy dissipation of the two systems is significantly different. As it is shown in Figure 16, the energy dissipated by each BF damper at each story level, is several times larger than the corresponding EBF system. This could be verified by the estimating area under the curve in which dampers in lower stories have the highest contribution to energy dissipation of the system. It is shown that that the maximum shear under the earthquake for both frames’ linking damper systems are the same; however, the contribution of the higher modes in the behavior of the conventional system is higher than the corresponding system with BF dampers



a) The EBF conventional system linking beam seismic response behaviour

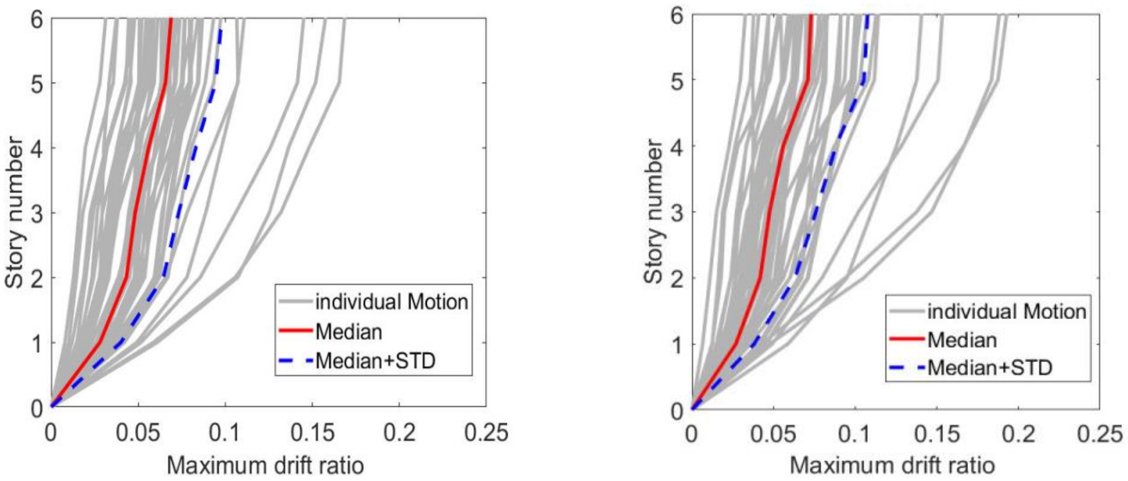
b) The linking beam response for the system equipped with BF damper

Figure 16. Seismic behavior of the convention and BF six-story systems under a specific earthquake loading

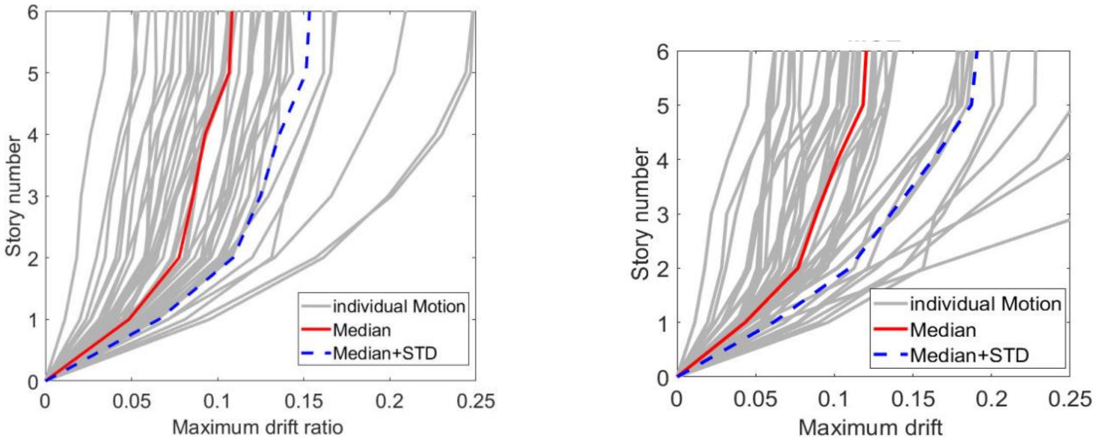
6. Nonlinear response history analysis results under for butterfly-shaped and conventional EBF systems

The behavior of the two six-story buildings under forty-four ground motions at two scale factors is studied in details. The results determine the difference in seismic performance of a system with butterfly-shaped dampers and conventional EBF under DBE and MCE hazard levels. The 176 computational models are developed and investigated for which the scale factors are selected based on the period of the structure. Figure 17 shows the behavior of butterfly-shaped and conventional systems for two seismic levels of DBE and MCE. The median and median plus one standard deviation is conducted and incorporated within the curves as it shown in Figure 17.

It is concluded that total drift ratio of each story is slightly higher for butterfly-shaped system due to slightly lower stiffness; however, the total story drifts for both systems are close, the implementation of the butterfly-shaped damper or simple conventional damper would results in similar total story drifts, which is justified due to similarity of the initial stiffness and total seismic mass. Ina addition, Figure 18 shows the maximum shear at the bottom of the two systems, under 44 ground motions.

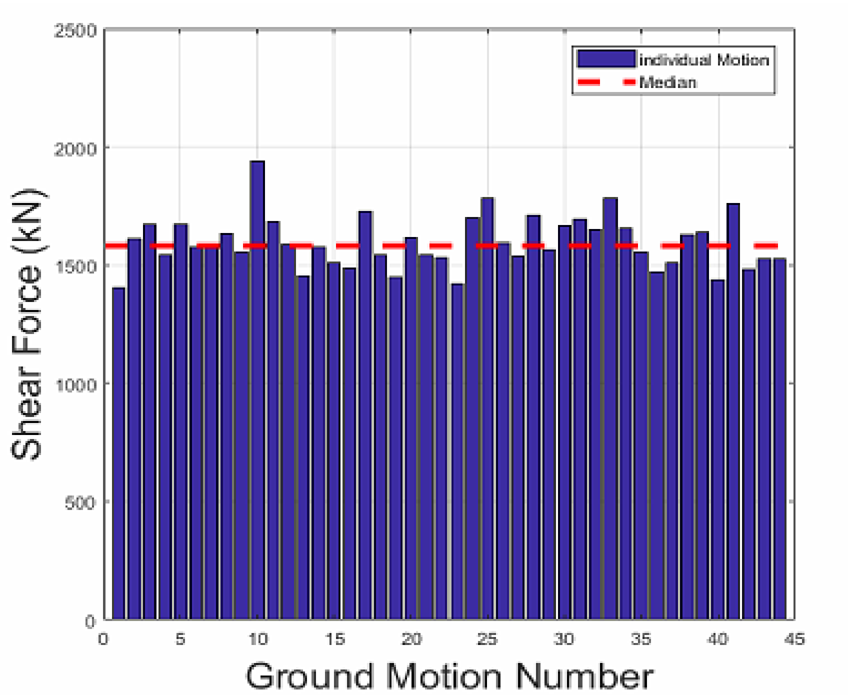


a) Conventional EBF system performance under DBE b) Butterfly-shaped damper system performance under DBE

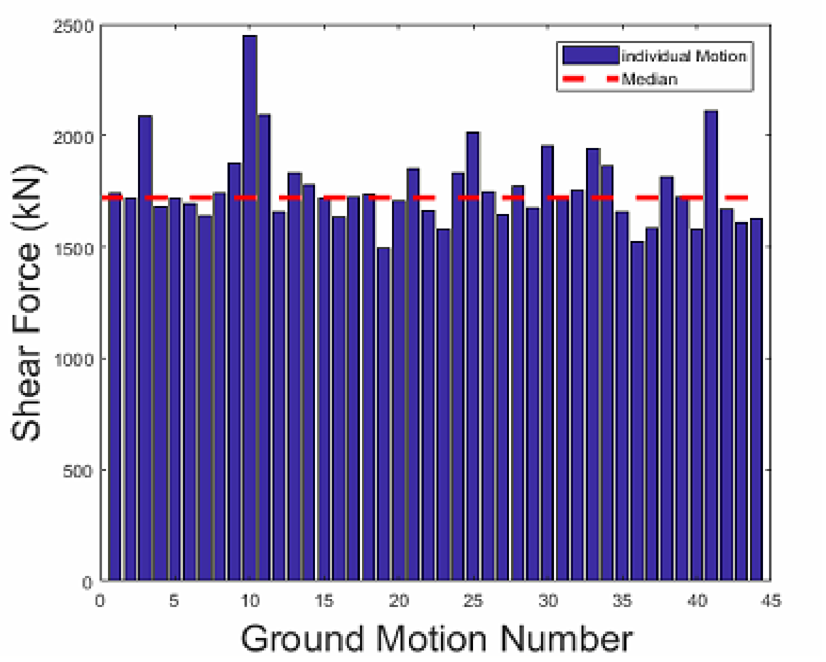


a) Conventional EBF system performance under MCE b) Butterfly-shaped damper system performance under MCE

Figure 17. The comparison of total story drifts for conventional EBF and butterfly-shaped damper equipped systems



a) Conventional EBF system

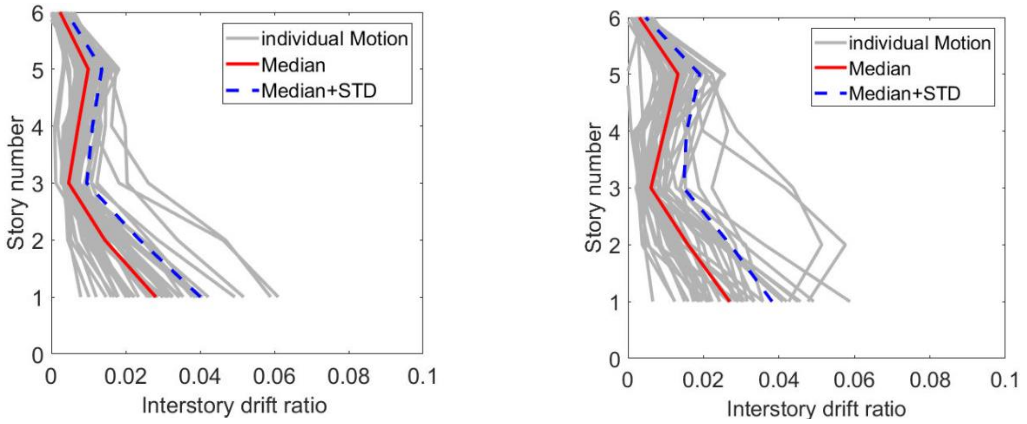


b) Butterfly-shaped damper system

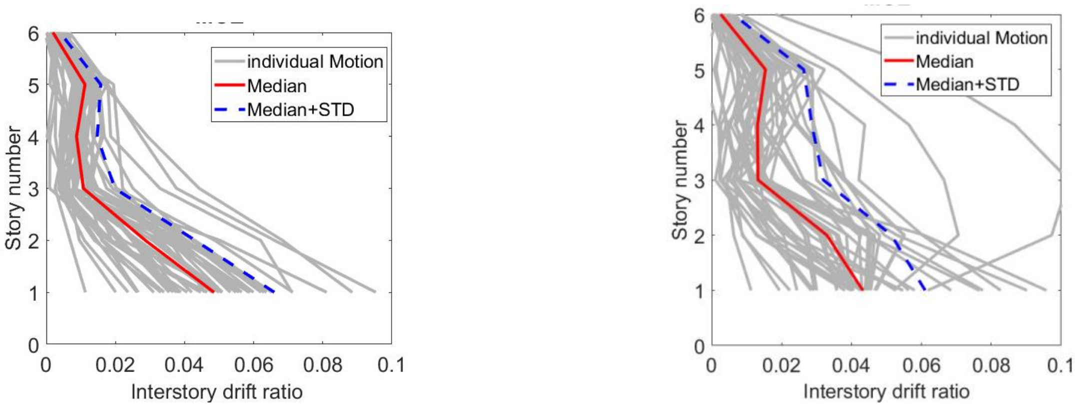
Figure 18. The comparison maximum total shear for two systems at 10% in 50 scale factor

The inter-story drifts for both systems are shown in Figure 19. It is concluded that the maximum inter-story is expected for the lower story levels, while the middle stories have the least inter-story drifts. The inter-story drift comparison of the butterfly-shaped system with conventional systems shows that the drifts are close due to the close total stiffness of the structures, and applied lateral loads. It is shown that the system with butterfly-shaped damper relatively reduces the inter-story drifts under both DBE and MCE hazard level especially for lower stories improving the overall performance of the structure and reducing the damages occurred to secondary structural elements.

The damper shear for both systems follow the similar trend with close values as it is shown in Figure 20. This indicates that both systems designed based on the same damper shear demands, are able to withstand the lateral load with the same yielding strength. The syustem equipped with butterfly-shaped fuse force curves exhibits more contributions form the lower stories to total resistance of the structure, while the higher stories have the least contribution to the total shear resistance compared with the conventional EBF system.

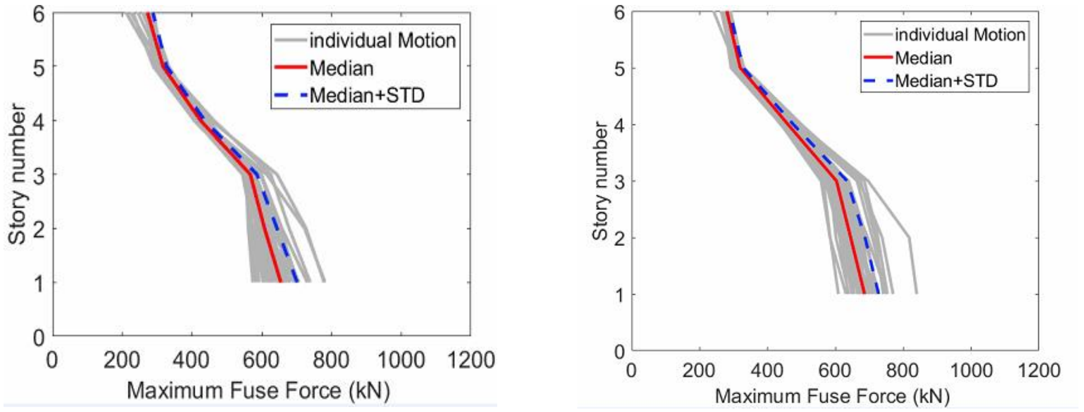


a) Conventional EBF system performance under DBE b) Butterfly-shaped damper system performance under DBE

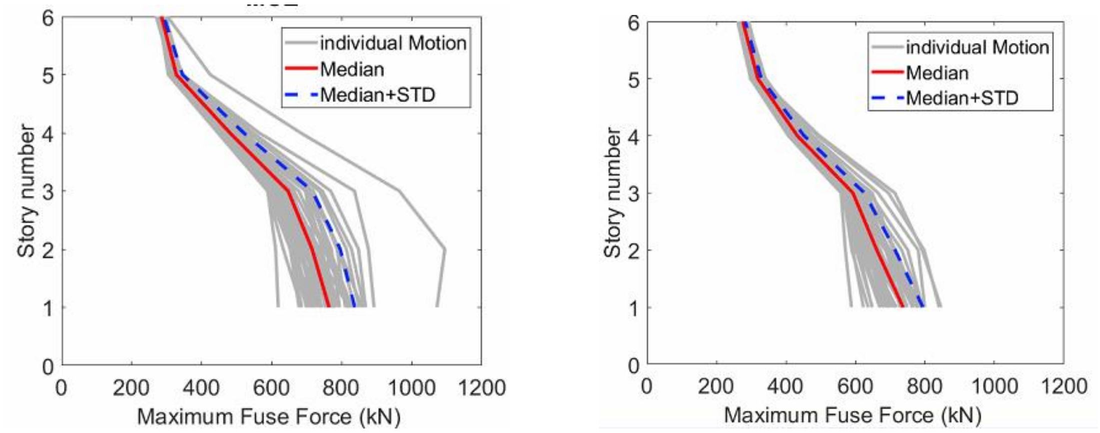


a) Conventional EBF system performance under MCE b) Butterfly-shaped damper system performance under MCE

Figure 19. The inter-story drifts for conventional EBF and butterfly-shaped damper equipped systems



a) Conventional EBF system performance under DBE b) Butterfly-shaped damper system performance under DBE

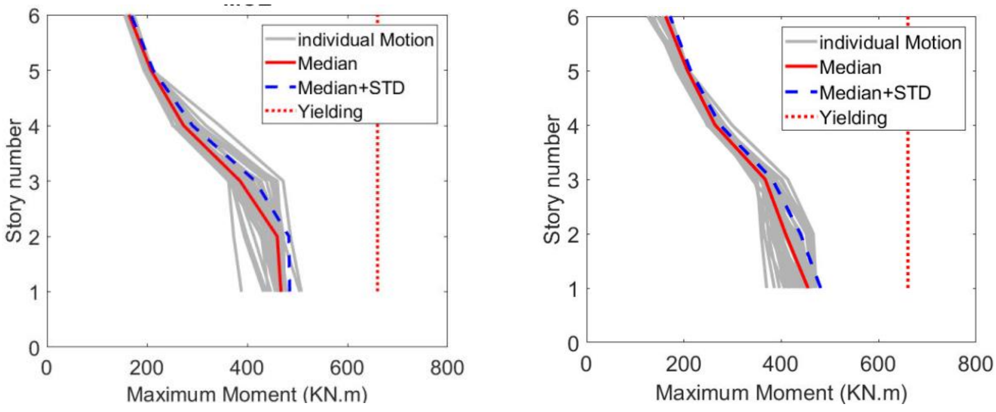


a) Conventional EBF system performance under MCE b) Butterfly-shaped damper system performance under MCE

Figure 20. The shear story force resistance comparisons for conventional EBF and BF damper equipped systems

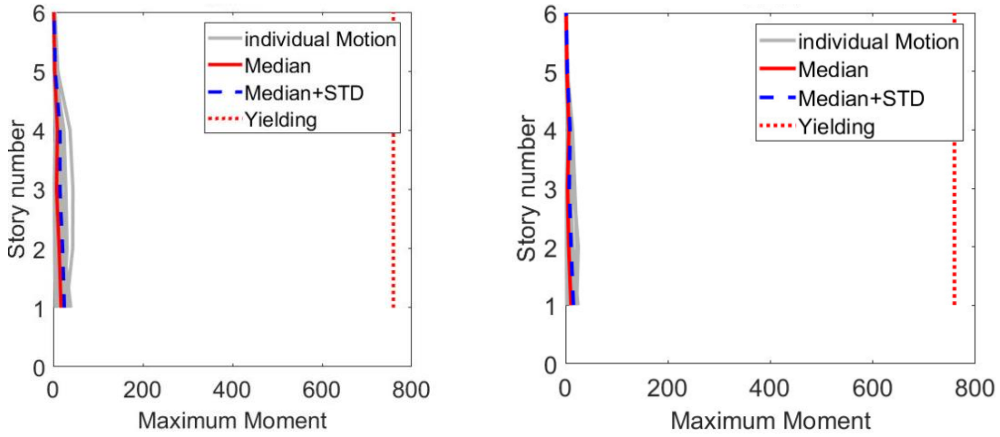
To further investigate the performance of conventional EBF and BF equipped structures, columns and beams are considered for monitoring the demands. It is shown that the maximum demand moments are tangibly less than the yielding limit state as it is determined in Figure 21. It is indicated that the assumption based on which the linking beams or BF dampers are designed to yield against the seismic load demands, while the rest of the structure remains in elastic region is valid. It is concluded that the conventional model generally has higher demands on the boundary elements, meaning that the boundary elements should be designed for larger loads, resulting in less economical design options. The general stiffness and strength performances of the system with the butterfly-shaped damper is close to the conventional computational models; however, the demands on the boundary elements are lower than the corresponding conventional model.

From the NRHA analysis, it is concluded that the structure with BF dampers is able to dissipate more energy within each story level, has less shear angles values, and less beam demands for the lower stories compared to the conventional EBF system. In addition to unique features of the BF equipped lateral resisting system, the replace-ability of these dampers could be considered as an effective solution for the structures located in seismic intensive areas.



a) EBF system’s beam performance under DBE

b) BF damper equipeed system beam performance under DBE



a) EBF system’s column performance under DBE

b) BF damper equipeed system column performance under DBE

Figure 21. Investigation of beams and columns elastic behavior

Conclusions

The strategically shifting the ductile mechanism from buckling and yielding in tension toward local flexure and shear yielding enhances the hysteretic performance behavior, and energy dissipation capability. The implementation of the new lateral resisting system equipped with butterfly-shaped dampers for multi-story prototype building are elaborated and compared with the conventional EBF system in this study. It is shown that new conFigureurations and design concepts that convert global shear deformations into local flexural yielding mechanisms could be beneficial for steel structures applications due to improving reducing the demands imposed on the other structural boundary elements. It is shown that the general stiffness and strength of the system with the butterfly-shaped link is close to conventional models; however, the demands on the surrounding boundary elements are lower than the corresponding conventional models, which could be beneficent for improving the seismic performance of the structural systems. It is determined that by controlling the flexural and shear yielding mechanisms to occur across the discrete segments of the steel, the structural system are able to effectively resist the buckling limit states at the primary stages of loading, and dissipate the energy more efficiently. For this purpose, after verifying the finite element modelling methodology and reduced order models, the results of the nonlinear response history analysis are achieved for 44 ground motions under two different MCE and DBE ground motion hazard levels. From 176 computational models, it is shown that implementation of the butterfly-shaped shear dampers in buildings with similar stiffness and strength to the conventional system leads to higher dissipated energy and larger hysteric curves compared. The general stiffness and strength of the system equipped with the butterfly-shaped damper is close to conventional prototype system; however, the demands on the boundary elements are over 30% lower than the corresponding EBF conventional model resulting in an efficient and economical design procedures for seismic intensive areas. It is shown that implementation of the butterfly-shaped dampers in buildings with similar stiffness and strength leads to higher dissipated energy and less pinched curves compared to typical eccentrically braced frame systems.

Acknowledgement

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Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request