PROBABILISTIC SEISMIC ASSESSMENT OF A MID-RISE ECCENTRICALLY BRACED STEEL FRAME EQUIPPED WITH BUTTERFLY-SHAPED DAMPERS

M. Zaker Esteghamati [(1)], A. Farzampour [(2)]

[(1)] *Graduate research assistant, Virginia polytechnic institute and state university, Mohsenzaker@vt.edu*
[(2)] *PhD, Virginia polytechnic institute and state university, afarzam@vt.edu*

Abstract

While modern code-conforming steel buildings can withstand seismic events without collapse through substantial inelastic action, the damages to structural members limit the building's post-earthquake functionality and safety. An efficient approach to minimize structural damage is to implement elements with large ductility and energy dissipation capability as shear fuses. Shear fuses are designed to protect the surrounding members from damages by yielding and are then easily replaced after the event imposing significant lateral forces. The butterfly-shaped dampers are a novel type of structural fuse with varying width that has been shown to improve structural energy dissipation and eliminate the high strain concentration in critical areas. However, a detailed risk-based assessment is needed to investigate their implementation and effectiveness in seismic retrofitting of mid-rise buildings.

In this study, the seismic performance of a six-story steel braced frame with supplemental butterfly-shaped dampers is investigated and compared with a conventional eccentrically-braced system using a probabilistic approach. Nonlinear finite element models are constructed using OpenSees simulation framework. Incremental dynamic analysis is then performed to derive seismic fragility and demand hazard curves in terms of the structure's global responses. The results show that butterfly-shaped dampers tangibly improve the structural seismic performance of the braced frame system compared to conventional systems at all considered performance levels. In addition, the improvement is more pronounced at larger drift demand levels associated with higher damage states. In particular, butterfly-shaped dampers reduces the mean annual frequency of exceeding the complete damage of the original building by a factor of 4 for the studied building.

Keywords: *Performance-based earthquake engineering; Structural fuse; Fragility assessment; Butterfly-shaped dampers; Incremental dynamic analysis*

1. Introduction

The tremendous economic and social impacts of the recent natural hazards on infrastructures, such as 2011 great east Japan earthquake and Tsunami and Hurricane Maria in 2017, attracted wide attention to increasing the resiliency of the built environment through novel lateral-resisting structural systems. In this regard, resiliency is often defined as the ability to sustain an external adverse condition and quickly recovering to the original state [1, 2]. The larger interest in resiliency is due to the fact that while modern buildings are designed for life safety objectives and expected to behave accordingly under severe earthquakes, they are susceptible to significant structural and non-structural damages due to inelastic action, which can increase their downtime, limit their post-earthquake functionality and incur large economic burdens [3].

Butterfly-shaped dampers are among recently developed structural shear fuses that provide a viable and economical solution to improving seismic resiliency. These dampers protect surrounding structural members by yielding during an extreme seismic event and are easily replaced afterwards [4], minimizing disruption to buildings' functionality. As shown in Fig 1, butterfly-shaped dampers are made of steel plates with diamond shape cutouts. The unique geometry of cutouts allows for bending strength to be aligned with the applied moment and hence, better distribute plasticity throughout the member [5, 6].

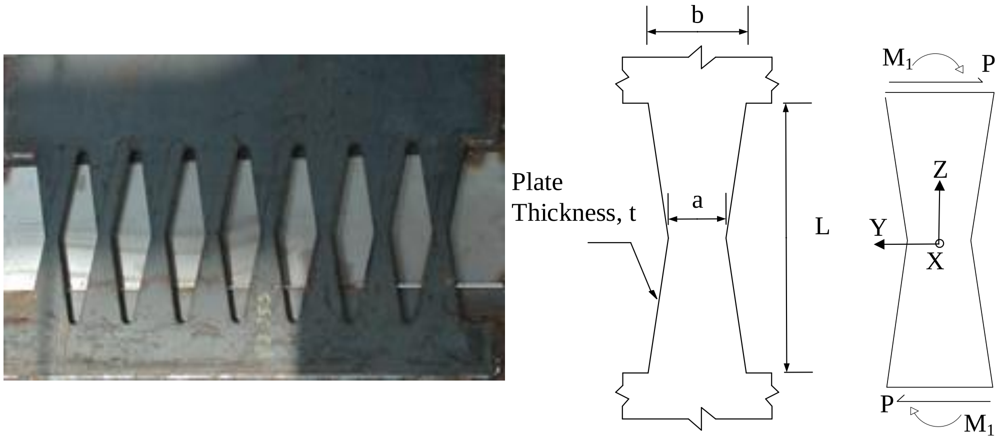

Fig 1 – Butterfly-shaped dampers

Despite the large body of literature addressing different types of dampers, only a few studies have investigated the seismic behavior of butterfly-shaped dampers. Ma et al. performed an experimental study on two series of specimens containing straight and butterfly-shaped links with different geometric configurations. The results showed that the plates with butterfly-shaped cutouts exhibited larger deformation capacity and reached higher strength at tension mode [7]. Lee et al. performed quasi-static tests on steel plates with different cutout shapes and showed that butterfly-shaped cutouts lead to two times larger ductility and energy dissipation than bar-shaped cutouts [8]. Along the same lines, by implementing slit fuses occasionally used in beam-to-column connection for improving energy dissipation, it is shown that the plastic deformation was mainly concentrated at the fuses, keeping the plastic deformation far from the connections [9]. In addition, Farzampour and Eatherton studied the effect of butterfly geometry on the load-resisting behavior of the fuses and concluded that taper ratios significantly impact yielding location and inelastic deformation capacity [6].

While previous studies provide insights on the seismic behavior of butterfly-shaped dampers from a component level perspective, additional research is needed to investigate the effect of these dampers on system-level behavior of multi-story buildings. Therefore, this study aims to provide a probabilistic assessment of a 6-story steel braced frame retrofitted with supplemental butterfly-shaped dampers using the performance-based earthquake engineering (PBEE) framework. Following PBEE formulation, quantitative measures are derived using conditional probabilities that relate structural damage to earthquake shaking intensity in terms of seismic fragility functions. Using fragility curves, mean annual frequencies of exceeding different performance levels are obtained and compared to the original building. To this end, nonlinear finite elements of the original and retrofitted buildings are developed in OpenSees simulation framework and validated against experimental results. Incremental dynamic analysis is then performed and fragility and seismic demand hazard curves are obtained to compare two buildings.

2. Numerical Modeling

2.1. Prototype building description

A 6-story steel frame with eccentric braces is adopted from the SEAOC manual [10]. The prototype building is assumed to be located in Los Angeles, California, USA, where it is subjected to high seismic hazard corresponding to site class D. As shown in Fig 2, the original building is then seismically upgraded by replacing the linking beams with butterfly-shaped dampers at each story. Story shear forces are taken from

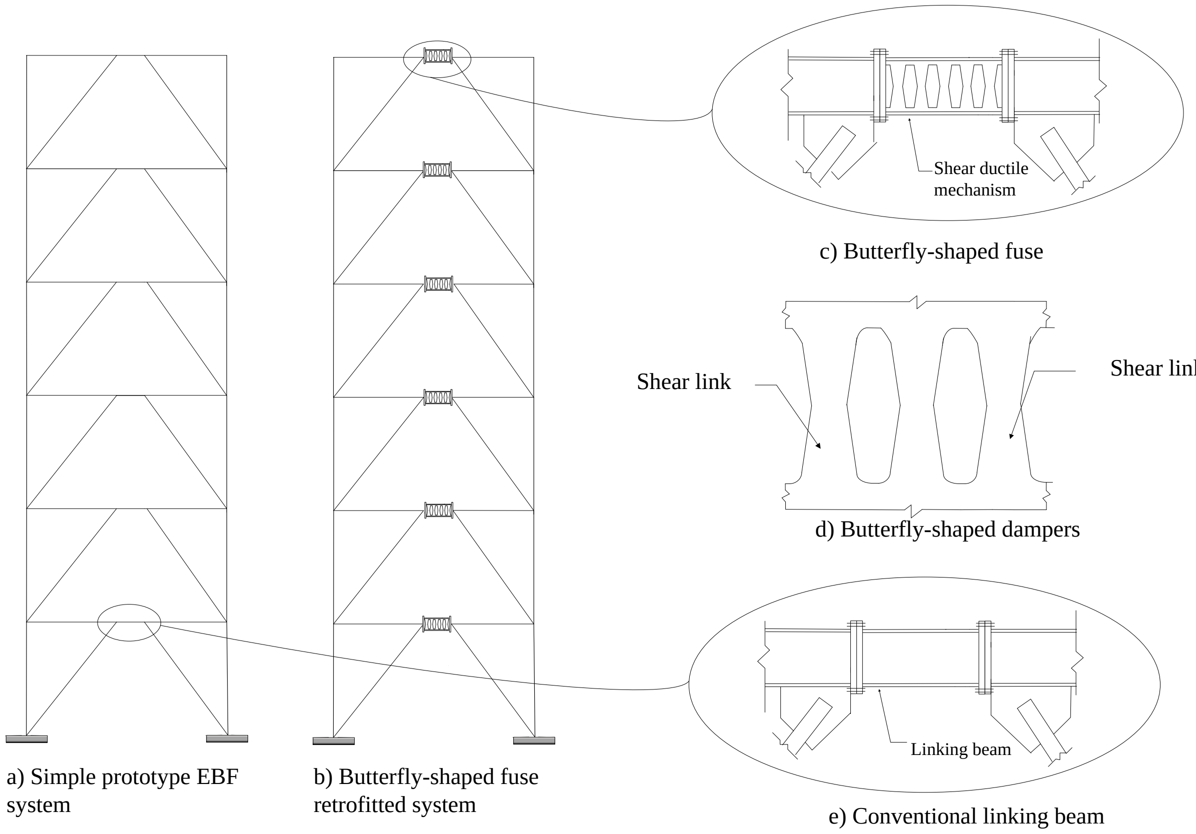

Fig 2 – Schematic representation of the original building (a) and retrofitted building (b) and the structural detailing

the SEAOC manual and used to design three groups of butterfly-shaped dampers for lower, mid and top stories. Following an approach described in [11], butterfly-shaped dampers are designed based on flexural yielding at quart-points across the link's length and prevention of lateral-torsional buckling. Each fuse comprises 10 links, where the width of the links at the ends and the middle is 12 cm and 3.8 cm, respectively. The plates' thicknesses are 2.2 cm, 1.7 cm and 1.2 cm for lower stories (1st to 3rd story), middle story (4th story) and upper stories (5th to 6th story), respectively. The detailing of the dampers is shown in Fig 2.

2.2. Nonlinear finite element modeling

Two-dimensional finite element models of the retrofitted and original buildings were developed in OpenSees [12]. Fig 3 shows the schematic configuration of the numerical models. In the Eccentrically Braced System (EBF) building, the linking beams were modeled using an elastic element with two plastic shear hinges at the ends, whereas all other members, such as beams, columns, and braces are expected to behave elastically. On the other hand, butterfly-shaped dampers of the retrofitted building are modeled using a series of displacement-based distributed plasticity elements [13] to account for the spreading of nonlinearity along the member's length. Each of these elements is then discretized to varying fiber sections to represent the change in geometry of the damper. Material nonlinearity is accounted for using Steel02 material [13] which uses the Guiraffre-Menegotto-Pinto model with 248 MPa yield strength and 0.05% strain hardening ratio. Similarly, the remaining structural members of the frame are modeled using elastic elements. The typical types of the connection used to attach the butterfly-shaped dampers to the boundary element are similar to the conventional systems; therefore, the shape fuse systems could be replaced and repaired accordingly [6]. The effect of gravity frames is accounted for by leaning columns. Each leaning column is connected to the main frame through rigid axial links and carries half of the weight of the interior gravity frames.

2.3. Verification of the modeling

To validate the modeling approach of butterfly-shaped fuses, first, a component-level high-fidelity model of the damper is developed in ABAQUS finite element software and compared with experimental results provided by Aschheim and Halterman [14]. Then, the same finite element model is compared to the macro-level OpenSees model of the butterfly-shaped damper located on the first story of the prototype building.

The experimental study consists of a beam with circular cut-outs with the top and the base beams made of TS14x10x5/8 and TS16x12x5/8, respectively [14]. The beam is then modeled in ABAQUS using solid elements with controlled hourglass and shear locking effect (C3D20R) to precisely capture the second-order behavior. A bi-linear stress-strain constitutive model is adopted to define steel material, where the yielding strength, strain-hardening modulus, and elastic modulus are 379 MPa, 1.38 GPa, and 200 GPa, respectively. To account for the first mode's buckling, an initial imperfection of 1/250 of the beam's length is applied. Fig 4.a shows the comparison of cyclic pushover analysis using the ATC 24 loading protocol [15]. Following the experimental setup geometry, the story shear force and drift of the FEM model are compared to 1.43 and 0.75 times of the beam shear and chord rotation of the experimental setting geometry. As Fig 4.a shows the difference between the average maximum strength values from the finite element model and experimental results is less than 5%, indicating that the numerical model is reasonably accurate. For example, the strength before and after buckling of the numerical model is 3.7% and 8.2% smaller than the experimental results, respectively.

The developed finite element model is then modified to represent the geometry and detailing of the butterfly-shaped damper located at the first story of the retrofitted building. Similarly, the modeling approach discussed in the previous section is implemented to simulate the same damper in Opensees and both models are subjected to AISC 341 loading protocol [16], following previous detailing recommendations [7]. As shown in Figure 4.b, the two models are in satisfactory agreement and represent a similar trace at both loading and unloading regions, where the average difference between cyclic results of the two models is less than 2%.

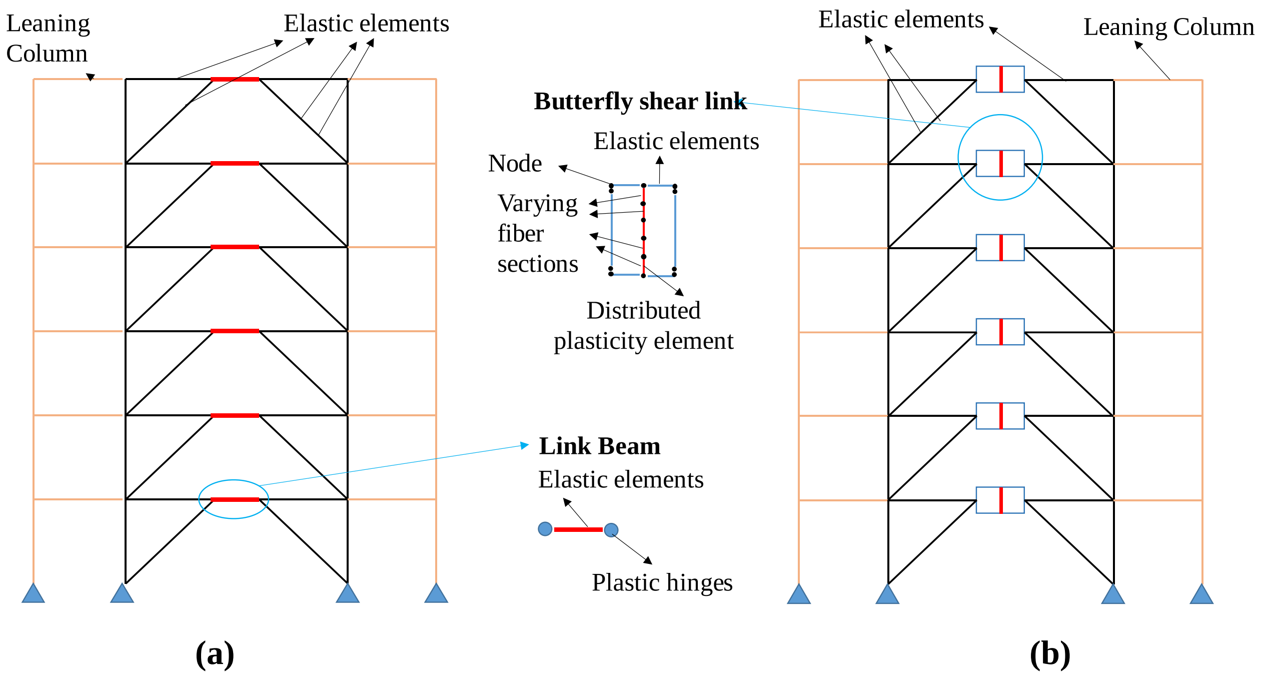

Fig 3 – Nonlinear finite element models' configuration for (a) original (b) retrofitted buildings

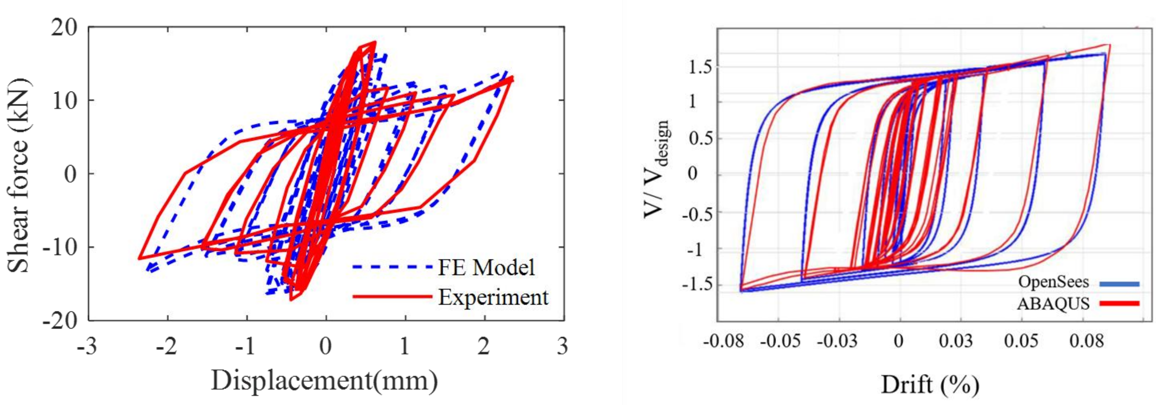

Fig 4 – Verification of the modeling approach: (a) comparison of ABAQUS and experimental results (b) OpenSees and ABAQUS model

2.3. Nonlinear time history analysis

Incremental dynamic analysis (IDA) is conducted by subjecting the numerical models to repeatedly scaled records of the standard FEMA P695 [17] far-field ground motion (GM) suite and performing nonlinear time-history analysis. This suite consists of 22 pairs of strong horizontal GM records with magnitudes between 6.5 to 7.6 and distance less than 10 Km and has been widely used in past studies to estimate the seismic risk of different lateral systems [18]. Spectral acceleration at the first mode of the structure (i.e. *Sa*) is taken as the GM's intensity measure (IM) and is increased at 0.1 g intervals up to 4 g to capture structure response from elastic to collapse state. For each IM level, the structure's global response is recorded in terms of maximum inter-story drift (IDR_{max}) and is post-processed to obtain IDA curves as shown in Fig 5. To summarize IDA curves information, median and 16th and 84th percentile curves (corresponding to IDR levels that exceed 50%, 16% and 84% of records, respectively) are shown as well.

Comparing Fig 5.a and 5.b, it can be concluded that the model with butterfly-shaped dampers maintains smaller drift values for a given IM level. For example, at 2% and 10% drift levels (commonly taken as serviceability and collapse performance levels for steel frames) the median *Sa* value of building with butterfly-shaped dampers is 60.4% and 48.7% larger than the original building, indicating that a larger earthquake shaking intensity is needed to achieve the aforementioned drift demands.

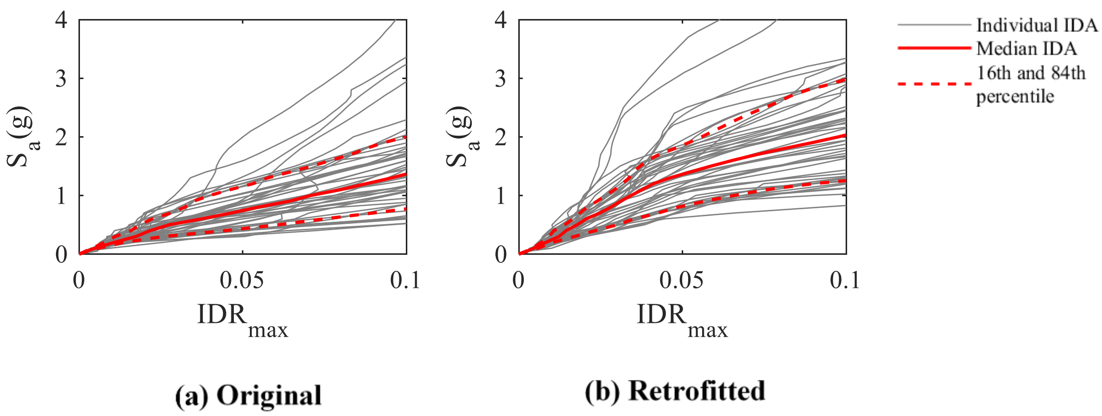

Fig 5 – IDA curves of the (a) original and (b) retrofitted buildings

3. Seismic performance assessment

3.1. Seismic fragility curves

Seismic fragility curves are conditional cumulative probability distributions that relate ground motion characteristics in terms of IM to the structural damage level. Following the common assumption of lognormality, the probability of exceeding a given level of EDP, *edp*, at an intensity level of *im* is calculated as follows:

$$P(EDP > edp|IM = im) = \Phi\left(\frac{\ln(\frac{x}{\theta})}{\beta}\right) \quad (1)$$

Where Φ is the standard normal cumulative distribution and θ and β are the median and standard deviation of fragility functions that are estimated from the nonlinear analysis procedure using the method of moments. Since a lognormal distribution only needs two parameters to be fully defined, the first and second moments of IDA observations ($\hat{\theta}$ and $\hat{\beta}$) are equated with the probability distribution parameters of θ and β as follows [19]:

$$ln\hat{\theta} = \frac{1}{n}\sum_{i=1}^{n} lnIM_i$$
$$\hat{\beta} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(lnIM_i - \frac{1}{n}\sum_{i=1}^{n} lnIM_i)^2} \quad (2)$$

Following HAZUS guidelines [20], fragility functions are developed for four different damage states of slight, moderate, extensive and complete corresponding to 0.3%, 0.67%, 2%, and 5% drift levels, respectively. In this regard, slight damage state denotes limited yielding of braces, minor cracks in welded components or deformation in bolted members, whereas moderate damage state refers to noticeable stretching and/or buckling of braces, reaching ultimate capacity in several members or connection. For higher damage states, extensive shows most of the braces and other members exceed yielding and exhibit permanent displacement. Partial collapse is possible and several members and connections exceed ultimate capacity. Lastly, complete damage state shows that most of the structural components reach ultimate capacity or several critical members have failed, resulting in partial or complete collapse of the building [20].

Fig 6 shows the fragility curves of the two buildings under different damage states. It can be concluded that at a given shaking intensity level, the building equipped with butterfly-shaped dampers has a lower probability of exceeding any of the considered damage states, and the difference is larger at more severe damage states. For example, the median *Sa* value exceeding extensive damage state is 50% larger for retrofitted building, whereas for complete damage state the difference increases to 81.2%.

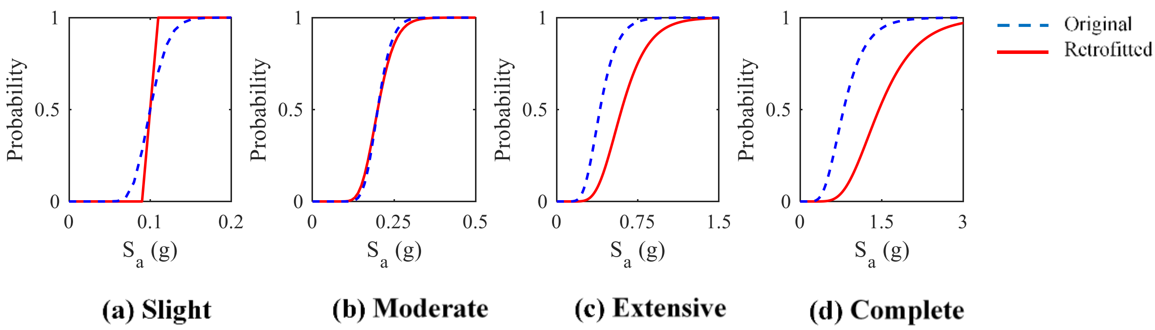

Fig 6 – Comparison of retrofitted and original building under different damage states

3.2. Seismic demand hazard curves

Seismic demand hazard curves are obtained by integrating over the product of the structure's fragility and the site's hazard curves to yield the mean annual frequency of exceeding different performance levels [21] as follows:

$$\lambda(EDP) = \int_{IM} G(EDP|IM) \, . \left| \frac{d\lambda(IM)}{dIM} \right| dIM \tag{3}$$

Where λ is the mean annual frequency (MAF) of exceeding a variable, G(EDP|IM) denotes the function fragility, and λ(IM) is the IM hazard curve. In this regard, MAF accounts for the full spectrum of the seismic hazard at the building site over a specific period of time, rather than a few discrete damage states [21,22]. Site-specific IM hazard curves are constructed based on the probabilistic seismic hazard assessment data for *Sa* available at the United States Geological Survey (USGS) database [23]. A polynomial regression is then fitted to hazard data of available periods in log-log space to obtain λ(IM) corresponding to the first mode period of the considered buildings [24].

Fig 7 shows the seismic demand hazard curves of both systems. It is clear that butterfly-shaped dampers reduce MAF of the original building and their impact is more pronounced at larger drift levels. For example, the MAF corresponding to extensive damage (i.e. 2% drift) of the retrofitted building is 2.22×10^{-3}, which is about half of the original building MAF value of 4.89×10^{-3}. On the other hand, for complete damage state (i.e. 5% drift level), MAF of the retrofitted building is 0.32×10^{-3} which is about one-quarter of the original building MAF value of 1.39×10^{-3}.

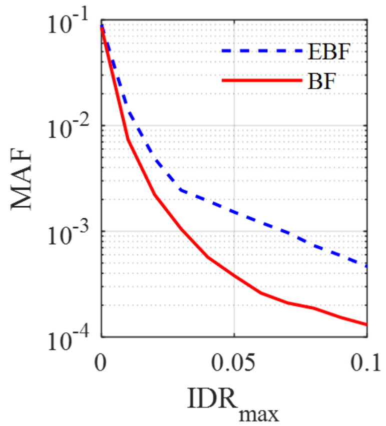

Fig 7 – Seismic demand hazard curves of the original (EBF) and retrofitted (BF) building

4. Conclusion

In this study, a novel type of structural dampers referred to as butterfly-shaped is numerically implemented in a multi-story eccentrically braced steel frame and the seismic performance of the upgraded system is compared to the original building. A finite element modeling technique using a series of distributed plasticity elements is proposed and validated against experimental studies. In addition, fragility and seismic demand hazard curves are derived. The results show that butterfly-shaped dampers improve seismic performance under all considered damage states and the impact is more significant at near collapse limit states. For example, the mean annual frequency of exceeding 5% drift level corresponding to complete damage state is 3.2×10^{-4} and 13.9×10^{-4} for the retrofitted and original buildings, respectively. This observation indicates that butterfly-shaped dampers effectively reduce the seismic risk of structures exceeding large drift demands.

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