Hysteretic Behavior of Beam-to-Column Connections Equipped with Buckling-Restrained Steel Dampers

Yashar Gholami[1], Behzad Shekastehband[1*]

[1] Department of Civil Engineering, Urmia University of Technology, Urmia, Iran

ABSTRACT

The combination of damage-controlled systems consisting of steel dampers with connections in steel frames reduces the damage to the main structural elements during earthquakes. In this study, two types of buckling-restrained dampers in moment-resisting connections between beams and columns under cyclic loading are numerically investigated. These dampers are the Jointed Arc Plate Damper (JAPD) and the Tube-in-Tube Damper (JTTD). To validate the finite element modeling, the results of numerical analyses of T-stub dampers were compared with experimental results, showing very good agreement between numerical and experimental results. By conducting cyclic analyses up to 4% drift on twelve damper models for various parameters such as different damper-to-beam yield strength ratio of the damper to the beam and the cross-sectional area of the damper, seismic performance characteristics including initial stiffness, moment resistance, ductility, and energy dissipation capacity are compared. According to the analysis results, the JTTD damper performs better than the JAPD damper, with moment resistance and energy dissipation of the JTTD model being approximately 10% and 5% higher than those of the JAPD model, respectively. Increasing the damper-to-beam yield strength ratio from 0.6 to 1.00 results in approximately a 35% increase in moment resistance of the models. In these models, increasing the cross-sectional area of the damper by 40% leads to a roughly 50% increase in connection moment resistance. The theoretical relationships estimate over 85% of the corresponding finite element analysis values, but for estimating the elastic stiffness of the models, the theoretical value should be divided by 3.5. Increasing the damper-to-beam yield strength ratio from 0.6 to 1.00 has no significant effect on energy dissipation, while ductility increases by about 25%.

KEYWORDS

Energy dissipater, Hysteretic behavior, Buckling-restrained, Plastic deformation, Ductility.

[*] Corresponding Author: Email: b_shekastehband@uut.ac.ir

1. Introduction

In the aftermath of the 1994 Northridge earthquake and 1995 Kobe earthquake, due to numerous unexpected failures of welded connections, it was recognized that fully welded moment connections exhibited inherent drawbacks. Numerous proposed solutions to the moment frame connection problem were attempted with the aim of moving the plastic hinge away from the face of the column. Solutions based on energy dissipation concepts that circumvented the need to develop the plastic moment of the beam were also proposed. To achieve more stringent seismic performance objectives, the design approach is to concentrate damage on disposable and easy to repair structural elements referred as structural fuses, while the main structure is designed to remain elastic or with minor inelastic deformations. ADAS and T-ADAS [1], and the honeycomb damper [2], are most commonly used passive energy dissipation devices that serve as non-structural reciprocating to absorb the input seismic energy and protecting the structural elements. A number of other alternative hysteretic energy dissipation systems, such as providing the connection scheme with seismic energy dissipation through connecting elements have also been proposed. These dampers can be strengthened through introducing buckling restrainers which provide sufficient rigidity for steel dampers in order to avoid the early shear buckling. The main motivation is to create a device that can reach the full yield strength, and to eliminate or significantly reduce plastic damage to the dampers. The current study examines the performance of two innovative types of buckling-restrained steel dampers employed as key energy-dissipating elements in beam-to-column connections.

2. Methodology

To explore the behavior of the beam-to-column connection with buckling-restrained steel dampers during an earthquake, the beam-column substructure, as shown in Fig. 1 (b), was extracted from the prototype structure in Fig. 1 (a). Twelve models are taken into consideration which can be categorized into two groups of Jointed Arc Plate Damper (JAPD) and the Tube-in-Tube Damper (JTTD). Each connection is characterized by different damper-to-beam yield strength ratio and cross-section area of the dampers. Details of the joints are illustrated in Fig. 2.

As beam and column are intended to remain elastic, the load path provided by all parts of the connectors, except damper must remain elastic to ensure full development of the damper's plastic mechanisms. H-400×400×13×21 mm section and an H-500×200×10×16 mm section adopted for columns and beams, respectively. The distance between the column center and the loading point is 3250 mm, both the beam length and column height being 3600 mm. Furthermore, high strength bolts of Grade-10.9 M36 are adopted.

The quasi-static cyclic load in accordance with the SAC test protocol [3] is applied to the reference point which was coupled to the loading surface of the beam tip.

The displacement boundary conditions contained pin supports at both ends of column (i.e. U1=U2=U3=0). Lateral restraints were utilized to prevent any unexpected instability and lateral torsional buckling of the connection specimens.

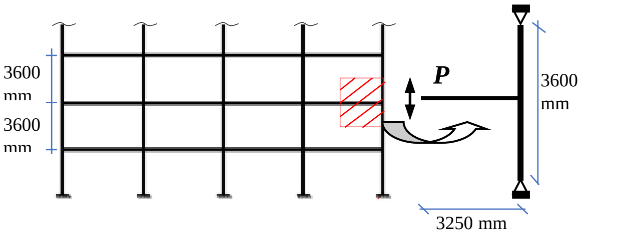
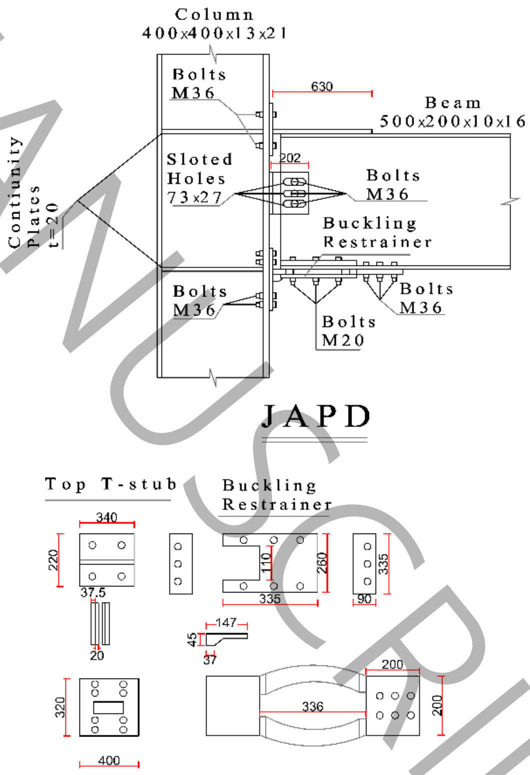
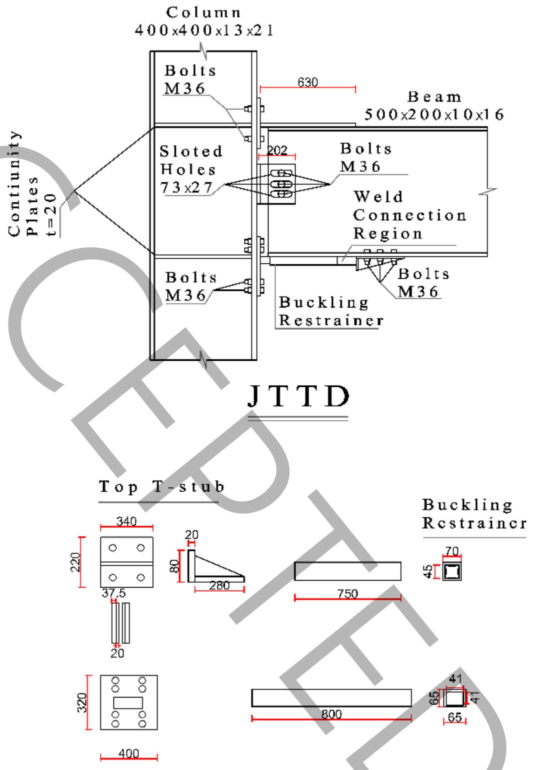


Figure 1. Substructures for seismic cyclic extracted from a prototype steel frame structure.



(a)



(b)

Figure 2. Details of the models: (a) JAPD; (b) JTTD.

The 8-node continuum solid elements with reduced integration, C3D8R, are used to model all parts (Fig. 3). The proper mesh density was obtained using the free element mesh technique. Further, a finer mesh was adopted in the connection zone. The interaction between welded components was modeled by the "tie" command. In order to achieve a balance between the accuracy and computational efficiency, finer mesh of approximately 15 mm is used only in areas where local buckling or plastic hinges occurs, i.e. at the T-stub type slit damper (TSD). Coarser mesh of approximately 25 mm is used for other parts of the beam and column. A minimal number of two elements through the thickness are used in order to improve the plastic strains and the global solution. Also, for the bolts a fine mesh is used. Moreover, for the parts in contact, master-slave types, a finer mesh was used for the slave ones.

Surface to surface contact interactions with finite sliding are employed for all contacting surfaces between the connector and the column/beam, between the bolts and the connected elements, between the damper and buckling restrainer as well as between the shaft and the nut of the bolts and the steel profiles. Contact interaction property is defined as Hard Contact. In the tangential direction, frictional contact between contacting pairs is defined with a coefficient of friction μ = 0.3. The tangential contact condition is modelled using the Penalty Method, which involves compatibility of the kinematic conditions between displacement, velocity and acceleration. Table 1 lists the material properties of components. For the material nonlinearity, an elastoplastic constitutive law based upon the von Mises yield criterion combined with Prandtl-Reuss flow rule is adopted. Combined hardening – which considers both isotropic and kinematic hardenings – is selected to represent hardening behavior.

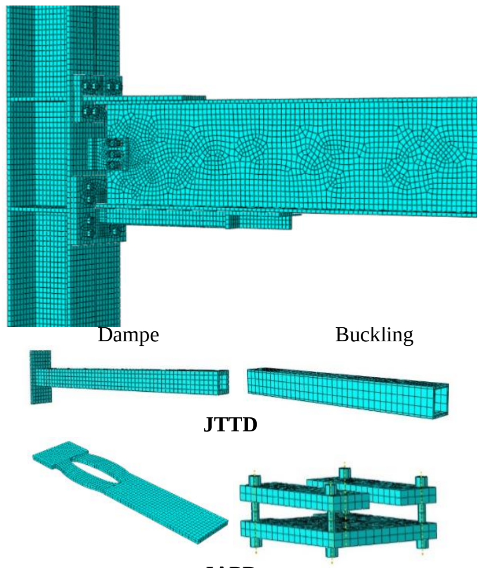


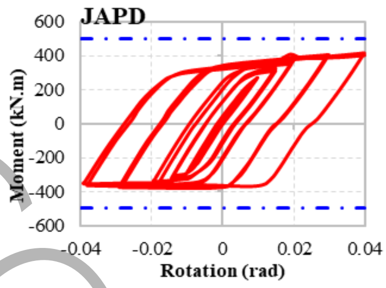
Figure 3. Three-dimensional finite element model for the studied connections.

Table 1. Mechanical properties of steel material

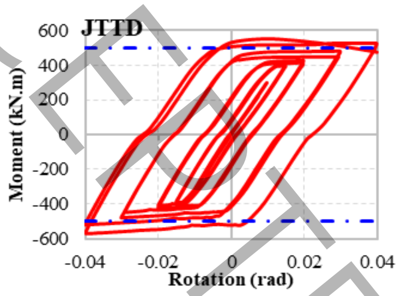
Model components	E (MPa)	σ_y (MPa)	σ_u (MPa)	ε_u(%)
Beam	206.89	258.03	440.05	30.6
Column	214.02	313.9	458.89	29.3

3. Results and Discussion

The hysteretic moment–rotation (M-Ө) curves of the models are shown in Fig. 4. The current approach is to ensure the satisfactory performance of such moment-resisting connections per AISC Seismic Provisions accommodating an inter-story drift angle of at least 0.04 rad with providing a flexural resistance of at least 0.80Mpb of the connected beam in SMFs. The moment and the inter-story drift angle indicated in Fig. 4 are calculated by the shear load at the tip of the beam multiplied by the length from the loading point to the column surface, and the displacement measured at the loading point divided by the beam length. The connections showed a satisfactory overall performance, characterized by stable and plump hysteresis loops under cyclic loading. JTTD model is found to have superior hysteretic performance over JAPD model with stable and repeatable behavior. Beams and columns with a plastic strain (PEEQ) of zero behaved in a purely elastic manner, as shown in Fig. 5.

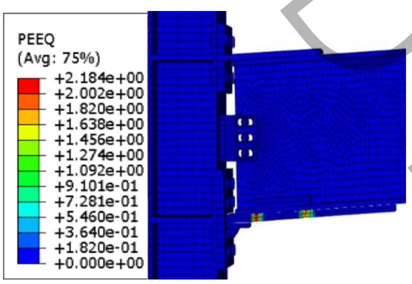


(a)

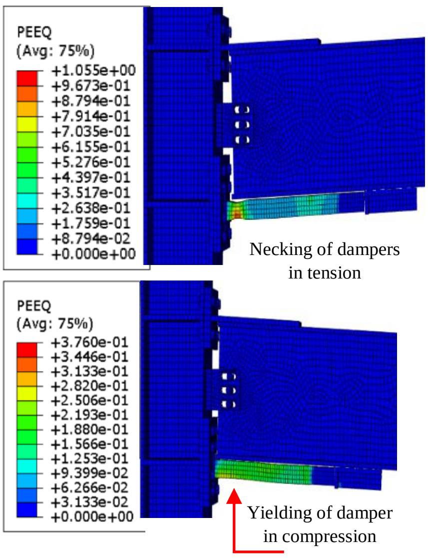


(b)

Figure 4. Moment-rotation hysteretic curves of the models: (a) JAPD; (b) JTTD.



(a)



(b)

Figure 5. Plastic strain distribution along with deformed shapes of: (a) JAPD; (b) JTTD.

For a given connection type, the magnitude of ultimate strength increased with increasing α parameter. The initial stiffness of the connections is not influenced by this parameter. The flexural strength value of the JTTD model is approximately 10% higher than that of the JAPD model, while the elastic stiffness values of the models are almost the same. The theoretical and numerical values of yield moment strength are close to each other; however, the theoretical elastic stiffness is much larger than the corresponding numerical values. The energy dissipation in the JTTD model is about 5% higher than the JAPD model. In both models, the reduction in energy dissipation for an increase in α value by 20% (from α=1 to α=1.2) is approximately 3%.

4. Conclusions

In this study, two buckling-restrained dampers consisting of Jointed Arc Plate Damper (JAPD) and Jointed Tube-in-Tube Damper (JTTD) have been numerically investigated under cyclic loading. Also, the effect of damper-to-beam yield strength and cross-section area of the damper were studied on the hysteretic behavior. Among the interesting results, the following are noted:

- For α=1 and β=1, JTTD damper unlike the JAPD damper, meets the requirements of AISC 341 for SMFs;
- By increasing the value of α from 1.0 to 1.2, the flexural strength of JAPD and JTTD models increases by 17% and 14% respectively. However, the JAPD model still does not meet the requirements of AISC 341;
- The ratio of theoretical flexural strength to numerical one in JAPD and JTTD models is 96% and 87% respectively. The corresponding values in the elastic stiffness of the models are 3.40 and 3.45. It is suggested that a value of 3.50 be used in practice;
- As the value of β increases from 0.1 to 1.4, the JAPD model can be utilized for special moment-resisting frames while meeting the requirements of AISC 341-22.

5. References

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