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Performance Evaluation of Curved-TADAS Damper on Seismic Response of Moment Resisting Steel Frame

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ABSTRACT

In this study, the performance of triangular added damping and stiffness (TADAS) dampers combined with curved dampers (Curved-TADAS damper) is evaluated in moment resisting steel frame (MRSF). These dampers are passive and install in the beam-column connection region. Variable parameters of this study involve the width of curved damper (50, 75 and 100 mm), the thickness of TADAS damper (5 and 10 mm) and the number of TADAS damper (2, 4 and 6). Evaluation of MRSF was performed using the finite element method by ABAQUS. Two different experimental studies were used in order to evaluate the validity of the numerical simulation method and a suitable agreement was obtained. The response of the frames in different modes was compared with parameters such as energy dissipation, strength, stiffness, hysteresis damping ratio, and ductility. In the end, the performance of the proposed dampers was compared with the curved damper. The results show that Curved-TADAS dampers reduce the structural responses to seismic loading and prevent structural failure due to the dissipation of a large amount of seismic input energy. The function of these systems is such that, by performing special deformations, they absorb and deplete a large amount of earthquake input energy of the structure.

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1. INTRODUCTION

Rigid and semi-rigid steel frames are usually used for construction in seismic zones. If the beam-to-column connections of these structures have accurate performance, they can experience adequate ductility against lateral loads [1-6]. In such structures, there are some limitations due to high ductility and stress concentration at the welded beam-column connection region [6]. Rigid frames have high resistance to lateral loads such as earthquakes. However, in the design of these frames, there are concerns about the number of failures associated with the collapse of beam-to-column connections under the influence of large earthquakes. The large stress concentration in welds can provide failure in connections; therefore, the resistance is reduced and the performance of structure undermines [7]. Based on recent research, it is reasonable to assume all connections to be semi-rigid. In all cases, the rigidity of connections can be considered to be between rigid and hinged. In fact, assuming that the connection is fully rigid or hinged leads to simplifying the structural analysis [8]. The semi-rigid connections consist of members and connections and that causes the complexity of interaction between them, especially when they are under cyclic loading. This type of frame exhibits sufficient ductility capacity against cycle loads [9]. After Northridge earthquake, different methods were proposed to build and retrofit steel frames, which can be noted in these ways [10]: (1) Achieving high ductility by controlling methods and welding materials, (2) Exit from the triaxial conditions by softening the areas around the welds by removing parts of the beam or column and reducing the degree of bracing, (3) Provision of new details for ductile connections with the aim of focusing the inelastic strain of the structure in the

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beams, instead of columns and joint components (satisfying the design principle of strong column and weak beam), (4) The weakening of beam flanges in certain locations, which allows for the creation of inelastic strains in areas far from the beam-to-column connection. (5) Strengthening of connection elements until it transmits inelastic strains of connection to the beam.

On the other hand, in recent years, various devices of energy dissipation have been used to reduce the maximum seismic response of buildings, bridges and other civil constructions [11-14]. Providing reliable mechanisms for the energy dissipation of a destructive earthquake is the key to protect structures against earthquakes. The use of these instruments causes inelastic deformations to restrict forces and provide the hysteresis energy dissipation for the structural system [15].

The idea of designing such a mechanism as a member to dissipation the earthquake energy in a way that the other main components remain stable has been introduced as an idea of building fuse. The idea of the structural ductile fuse is first introduced by Roeder and Popov [16] for eccentrically braced steel frames.

In contrast to earlier seismic design methods that most of the energy dissipated by the earthquake with inelastic deformation of certain structural zones (usually both ends of beam and column in MRSF), in the passive control system, this energy is transmitted to special elements called seismic dampers. A number of systems used for energy dissipation include frictional, steel, viscoelastic, and liquid viscous dampers. These passive energy dissipation systems absorb seismic energy and improve the seismic performance of structures by modifying the structural dynamic characteristics [17].

Various studies have been carried out on the use of damper in steel structures. Benavent-Climent [18] designed a type of bracing seismic damper for structural strength against lateral loads. The damper was assembled in the form of tube-in-tube through the hollow steel section. The external hollow section of the damper was made by a series of strips with regular gaps that were welded to the inner hollow section. The features of this type of damper are good buckling resistance, low cost, and easy to replace after an earthquake. In the mentioned research, the proposed damper was subjected to cyclic loading and compared with conventional dampers. The test results showed that the proposed damper has stability hysteretic characteristics and its energy dissipation is suitable.

Kang and Tagawa [19] introduced a new type of vibration control system based on the seesaw mechanism with liquid viscous dampers. The proposed vibration control system consists of three parts: seesaw, brace and liquid viscous dampers. In this system, only tensile force appears in brace members, so the buckling problem of braces is negligible. In this research, seismic response analyses were conducted for a different number of floors in MRSF with and without dampers. A comparison of analyses results shows that the proposed energy dissipation system has a high potential for improving the structural response.

Piedrafita et al. [20] introduced a new type of buckling restrained brace (BRB) as a new energy device for earthquakes retrofitting of building. In this type of BRB, the steel yielding core is modular. Comparison between the new and conventional BRB experimental results under cycle loading illustrates the fact that in both systems, the energy dissipation is almost the same.

Oh et al. [21] evaluated the seismic behavior of column-tree moment connections. This system is one of the moment resisting systems that are recently used in steel structures. The focus of this study was on the weak axis of the column. Two connections with a reduced beam section and a tapered beam section were investigated. A comparison of these two specimens showed that the RBS specimen had stable and ductile behavior.

Tahamouli Roudsari et al. [22] evaluated the response of RC buildings retrofitted with ADAS and TADAS yielding dampers. The results show that the use of ADAS and TADAS dampers in concrete frame can increase the bearing capacity and hardness. Ghaffary and Karami [23] evaluated the framework for virtual hybrid simulation of TADAS frames using OpenSees and ABAQUS. Comparison of modeling results with experimental results showed that the proposed method can be very accurate and close to reality in evaluating structural response. Garivani et al. [24] investigated seismic behavior of steel frames equipped with Comb-Teeth metallic yielding dampers. The behavior of Comb-teeth damper (CTD) has been studied numerically and experimentally. The results showed that this damper has a high energy dissipation capacity and a high plasticity ratio. Farsangi et al. [25] evaluated seismic performance of a resilient low-damage base isolation system under combined vertical and horizontal excitations. The results of nonlinear dynamic analysis showed that when the structure is exposed to multi-directional earthquake, the superstructure equipped with telescopic column has a higher safety margin than conventional dampers. Saghafi and Golafshar [26] investigated reinforced concrete frames equipped with TADAS dampers. The results showed that the seismic response of the retrofitted frame was significantly improved compared to the non-retrofitted state. Also, the drift of 4, 7 and 10 story frames decreased by 54, 56 and 55%, respectively. Hsu and Li [6] evaluated experimentally the effect of controlled buckling mechanisms on the behavior of steel frames with knee braces. Frames performance was evaluated under cyclic loading. The results showed that the knee braced moment resisting frame had a very good performance in both in-plane and out-of-plane directions. Palermo et al. [27] investigated crescent-shaped braces for the seismic design of building structures. In order to understand the mechanical behavior of this system, a comprehensive numerical and experimental study was carried out. A t the end, the design formulas for this system were presented and the ductility, energy dissipation, and buckling were evaluated. Finally, an experimental investigation by Hsu and Halim [28] that is related to the subject of this research is presented. In this experimental study, a new type of steel curved damper is proposed to improve the seismic performance of moment resisting steel frame (MRSF). The dampers are located between the beam and column. The behavior of the dampers depends on the length and angle between the two ends. In order to evaluate the effect of the curved damper on structural behavior, a series of cyclic loading tests were performed on moment resisting frames with different curved dampers angles. The results showed that the frame strength increased by reducing the damper angle. It was also observed that the strength, hardness and energy dissipation of the steel frame are significantly improved despite the dampers.

The ductility of the proposed damper by Hsu and Halim [28] may be low due to its early buckling and the lack of sufficient space for deformation. Hence, in the present study, the seismic response of MRSF is investigated using combined innovative dampers (Curved-TADAS damper). The purpose of choosing this type of damper is to improve the ductility and the strength of the curved dampers concurrently (Figure 1). This paper evaluates the performance of curved and triangular added damping and stiffness (TADAS) damper simultaneously on seismic response of MRSF. In this regard evaluation of geometric properties of this damper is the most important purpose of this study. The most performance of this damper is that the energy transferring to the structure leads to yielding the damper; so that the entire steel volume of the dampers yields before yielding the elements of the existing structure.

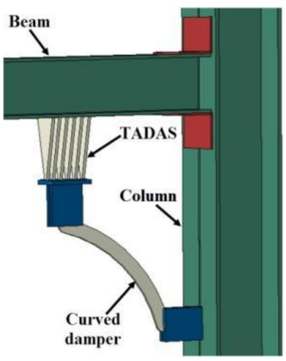


Figure 1. The proposed Curved-TADAS damper

2. STUDY PROCEDURE

The major reason for the use of passive energy dissipation devices in structures is to limit the destructive fractures in structure members. Among the various passive energy dissipation devices systems available, hysteric steel dampers effective and economical mechanisms to deplete earthquake energy which is obtained through the inelastic ductility of steel materials. As mentioned the present study investigates MRSF with Curved-TADAS damper. This type of damper can be easily repaired after the earthquake as a fuse element. The geometric of the proposed system has evaluated numerically by the finite element method (FEM). The variable parameters of this study involve the thickness of the TADAS damper (5 and 10 mm), the width of the curved damper (50, 75 and 100 mm) and the number of TADAS dampers (2, 4 and 6). Thus, a total of 19 finite element-finite element models have been simulated according to Table 1 and the response to cycle loading has been evaluated. The examined frame and the position of the proposed damper in the beam-column connection zone are presented in Figure 2. This damper is located between the two ends of the frame. The length and the height of the frames are 4.5 m and 2.5 m, respectively.

3. FINITE ELEMENT SIMULATION

In order to investigate the efficiency of curved-TADAS passive dampers embedded in the beam-to-column connection, the models were simulated in ABAQUS software [29]. The elements of studied frames include beam, column, angle, curved-TADAS damper and gusset plate for connecting damper to beam and column. The solid technique was used to simulate all sections. The behavior of elements is also three-dimensional and deformable. Deformable element is one of the five elements used in ABAQUS for modeling ductile members in 3D and 2D spaces. The steel grade of St37

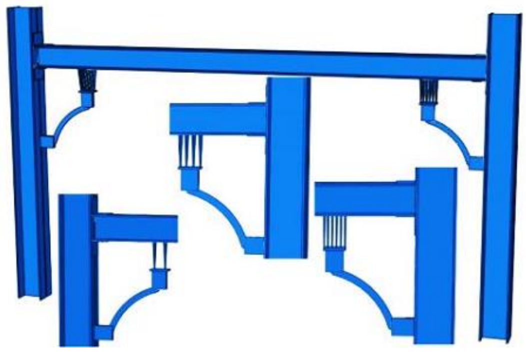


Figure 2. Geometric properties of the studied frames and position of the damper in the beam-to-column connection

was used for all the components of the frames. Top and seat angle connection size is considered 130×130×12 mm. ATC-24 [30] protocol loading history was used. The loading protocol is shown in Figure 3. Nonlinear static analysis has been used to analyze the models. The boundary conditions used in the modeling of beam-to-column connections in MRSF are considered so that the behavior of the semi-rigid beam-column connection can be evaluated against lateral loads.

Tie constraint is used to simulate the interaction between the surfaces. This constraint is one of the practical constraints in civil engineering, which can be used to integrate steel, in which both are modeled with solid elements [29, 31].

One of the most important parts of ABAQUS software is the mesh definition. In finite element analysis of this study, at first, models analyzed with large elements and one of the output quantities at a desired point of the model were recorded (for example maximum stress). Then the elements are diminished and the problem analyzes again. The process of subtraction of the elements continues so that the difference between the results is very low. The selected mesh is sufficiently good to ensure that the applied forces are calculated exactly. The optimum mesh size was selected 25 mm (Figure 4).

TABLE 1. Parameters of the analytical models

Curved damper width (mm)	TADAS damper thickness (mm)	TADAS Damper number	Contraction
-	-	-	No Damper
		2	W:50 2D t:5
	5	4	W:50 4D t:5
		6	W:50 6D t:5
50		2	W:50 2D t:10
	10	4	W:50 4D t:10
		6	W:50 6D t:10
		2	W:75 2D t:5
	5	4	W:75 4D t:5
		6	W:75 6D t:5
75		2	W:75 2D t:10
	10	4	W:75 4D t:10
		6	W:75 6D t:10
		2	W:100 2D t:5
	5	4	W:100 4D t:5
		6	W:100 6D t:5
100		2	W:100 2D t:10
	10	4	W:100 4D t:10
		6	W:100 6D t:10

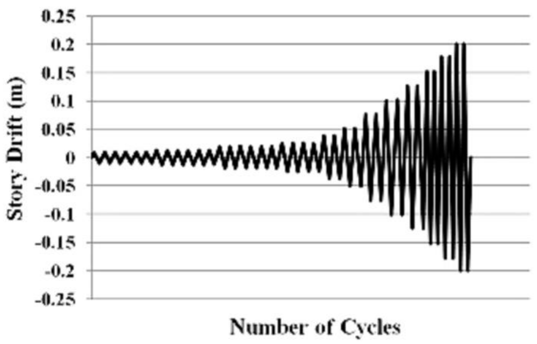


Figure 3. ATC-24 Loading history protocol [30]

4. VERIFICATION

Two different experimental studies were used in order to verify the validity of the simulation method. At first, the experimental study of Hsu and Halim [28] was selected to verify the used simulation method of the curved damper. As noted earlier, in this experimental study, a steel curved damper was introduced to improve the seismic performance of MRSF. The dampers were placed between the beam and column zone. In order to investigate the effect of curved dampers on structural behavior, eight different steel frames were tested under cyclic loading. The frame length and the column height are 4744 and 2520 mm, respectively.

The L2-60 frame was selected for verification of this study. In this specimen, e_b ،e_c and L are 845, 845 and 537 mm, respectively. Also, the beam-column connection is semi-rigid. One of the examined frames in the study of Hsu and Halim [28] is shown in Figure 5. More information about the material and the details of the test can be found in literature [28]. Finite element model L2-60 frame is shown in Figure 6. Also the load-displacement curves of the L2-60 frame are shown in

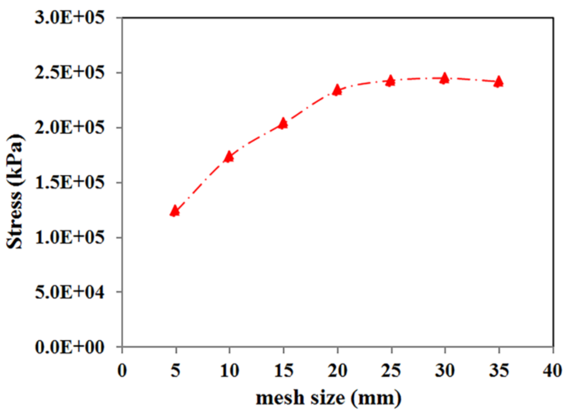


Figure 4. Mesh size optimization in ABAQUS

Figure 7. As it is seen, the strength and deformation values corresponding to the experimental and numerical samples are in good agreement. Also, comparison between experimental and numerical study were presented in Table 2 and the numerical and experimental results were compared to each other in terms of percentage.

The experimental study of Oh et al. [32] is the second selected experimental study to verify the used method in simulating the TADAS damper. The performance of the beam-to-column with a new damper was investigated in the mention study. Four beam-to-column connections were tested in full scale. In the first and second modes, the slit dampers were used at the connection (D1 and D2), in the third case, the presence of the composite floor slab with slit damper was investigated (DC2), and in the fourth state, a beam-column connection without damper was evaluated (W).

The beam and column sections are H-582×302×12×17 and H-400×400×21×21, respectively. The dampers are mounted at the bottom of the beam. Figure 8 shows the details of the beam-column connection with the damper. Specifications of the specimens of Oh et al. study are summarized in Table 3. To validate the simulation used method in this study, the specimen D1 was selected. The parameters presented in Table 3 are shown in Figure 9. More information about the material and the details of the test can be found in literature [27]. The Damper deformation and Von Misses stresses of the D1 specimen is shown in Figures 10 and 11, respectively. With regard to the load-displacement cycles shown in Figure 12 and comparing

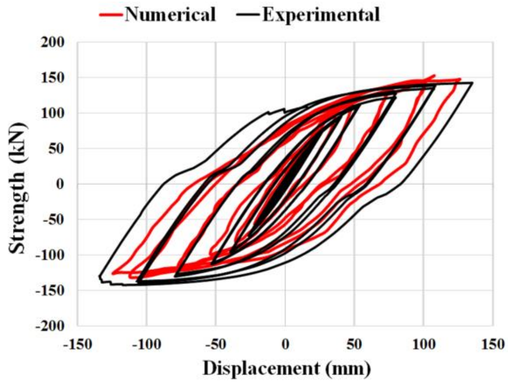
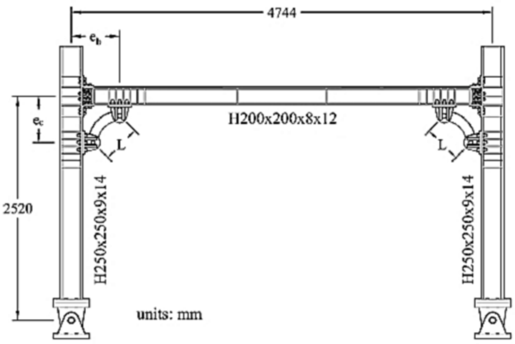
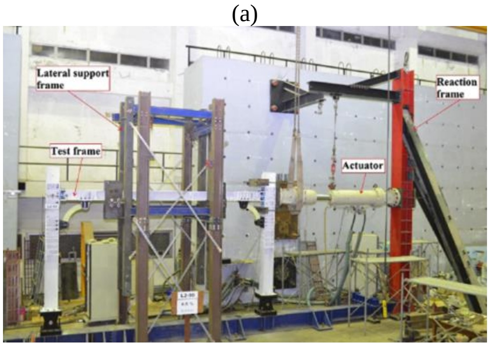


Figure 7. Strength-displacement for L2-60 frame



(a)



(b)

Figure 5. Test set-up a: Geometric properties b: test set up [28]

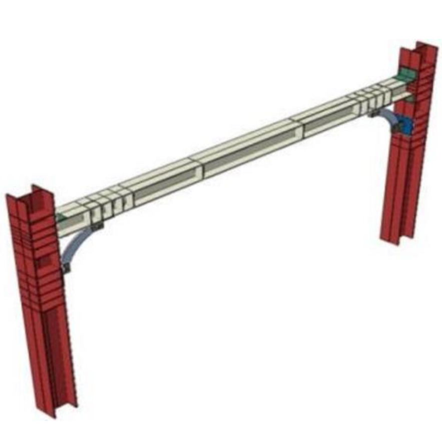


Figure 6. L2-60 frame (Finite element model)

TABLE 2. Comparison between experimental and numerical study

Hsu and Halim [28]	Numerical	Experimental	Error (%)
Dissipation energy (kN-m)	126	136	7.94
Strength (kN)	152	149	1.97
Hysteresis damping ratio (%)	26.6	26	2.26
Ductility	5.21	5.6	7.49
Oh et al. [32]	**Numerical**	**Experimental**	**Error (%)**
Dissipation energy (kN-m)	413.5	431.6	4.38
Strength (kN)	290.5	293	0.86
Hysteresis damping ratio (%)	35	36.3	3.71
Ductility	5.4	5.27	2.41

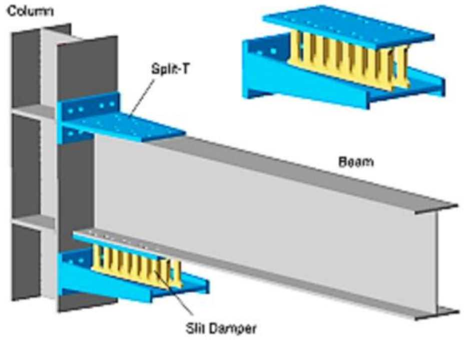


Figure 8. Details of the beam-column connection with the slit damper [32]

TABLE 3. Specifications of experimental specimens [32]

Specimen	Slit damper					Floor slab
	B (mm)	t (mm)	H (mm)	r (mm)	n (EA)	
D1	30	19	100	20	16	None
D2	40	19	100	20	16	None
D2C	40	19	100	20	16	Yes
W	Welded moment connection					None

the experimental model and the numerical model simulated by ABAQUS software, it is observed that the experimental and numerical results have good agreement. So, the results of the method used in this study, which is performed using ABAQUS, have relatively good correlation with the experimental results. Also, in Table 2, comparison between present study results and Oh et al. [32] study in terms of dissipation energy, strength, hysteresis damping ratio and ductility were presented.

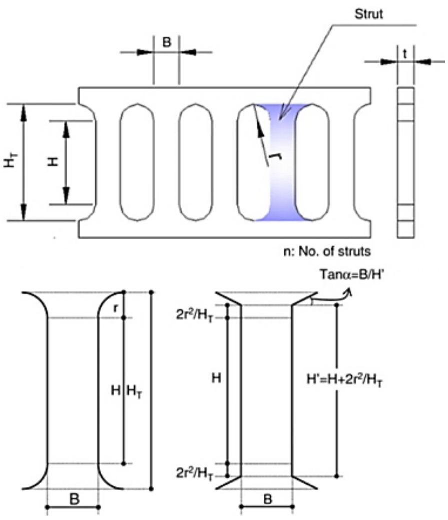


Figure 9. The geometric shape of the slit damper [32]

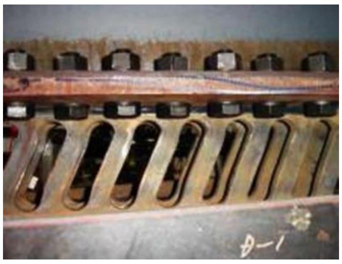


Figure 10. Damper deformation of D1 specimen [27]

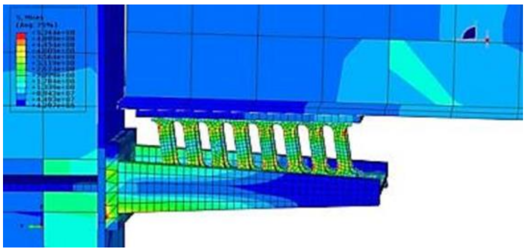


Figure 11. Von Misses stress of D1 specimen (ABAQUS model)

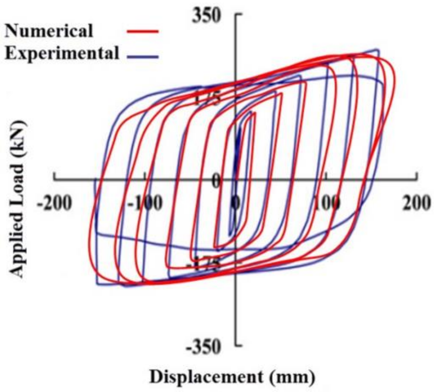


Figure 12. Load-displacement for D1 specimen

5. RESULTS AND DISCUSSION

5. 1. Energy Dissipation

After simulating and analyzing the studied frames using the FEM, the results are shown in the form of cyclic load-displacement curves. It should be noted that after presenting outputs, optimal modes selection is done according to the energy dissipation, strength, effective stiffness, hysteresis damping ratio and ductility.

Stress distribution and deformation in some investigated MRSF with different curved-TADAS dampers are shown in Figure 13. In all of the examined frames, the yield points have been observed in the proposed dampers. The curved-TADAS dampers dissipated seismic energy by absorbing inelastic deformations and prevented the transferring of seismic energy to the main members of the structure. Therefore, these dampers can be used in the beam-column

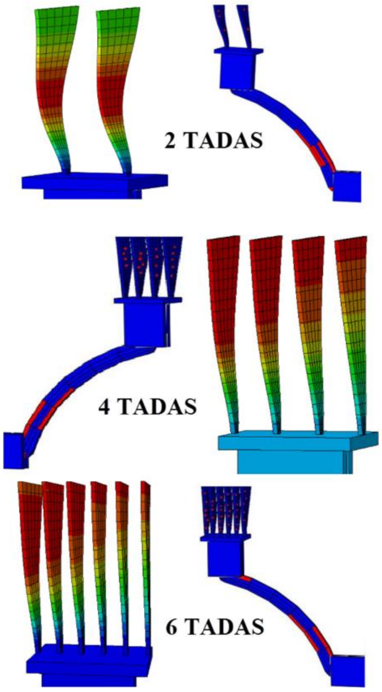


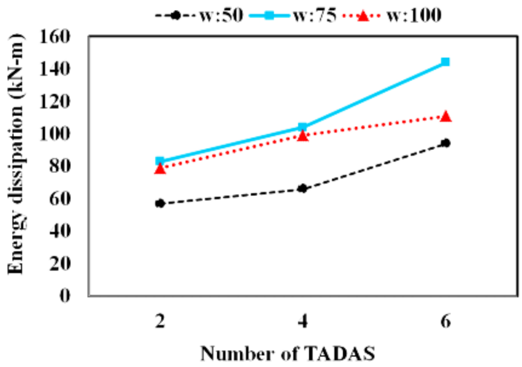
Figure 13. Stress distribution and deformation in some investigated MRSF with different curved-TADAS dampers

connection to prevent brittle fracture of the connections. The mechanism of damping in the curved-TADAS damper is such that before yielding of structural elements, the damper blades and the curved part yield and less amount of energy apply to the main structural elements. By reducing the failure in the main structural elements and focusing the failure in the dampers, the replacement time of the damaged elements will be greatly reduced, and as a result, the time of stopping the operability of the structure will be decreased.

According to Figure 14, increasing the number of TADAS plates (blades) in the proposed dampers has increased the energy dissipation of moment frames. In other words, the dampers with more plates (blades) have better efficiency. This is especially evident when the curved damper width is 75 mm. The plates of TADAS dampers with increasing the stiffness and damping of the structural system, improve the frame's strength against hysteresis loads.

Hysteresis loops for a number of studied frames are presented in Figure 15. Hysteresis energy means dissipating energy by nonlinear deformation loops and it is shown by the area of force-deformation curves. The comparison of energy dissipation is presented in Table 4 and Figure 16. The use of curved and TADAS dampers simultaneously has increased the energy dissipation of frames by 1.41 to 3.69 times compared to those in which the damper was not used. The mention increasing is dependent on TADAS thickness, number of TADAS and curved damper width. The highest energy dissipation was observed in a state where a curved damper with a width of 75 mm was used along with 6 TADAS dampers with a thickness of 5 mm (W:75 6D t:5). Also, the proposed damper around the beam-column connection region has caused the plastic hinge to occur in the farther region of the connection.

Generally, the results of energy dissipation of the frames examined indicate that the energy transmitted to the frames with proposed damper is merely due to yielding and nonlinear behavior of dampers so that the entire steel volume of the dampers yields before the existing structural.



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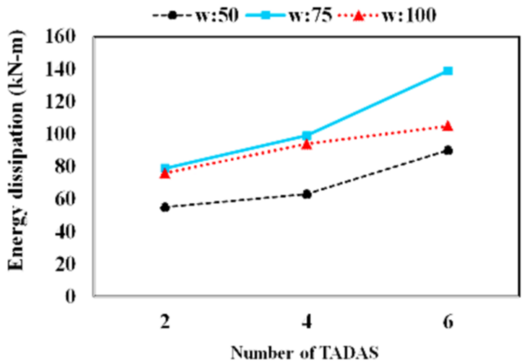
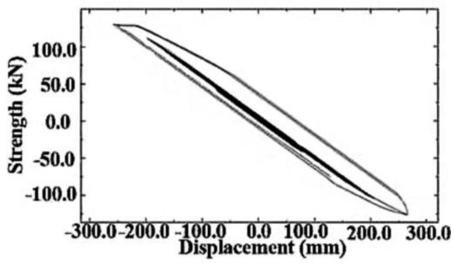
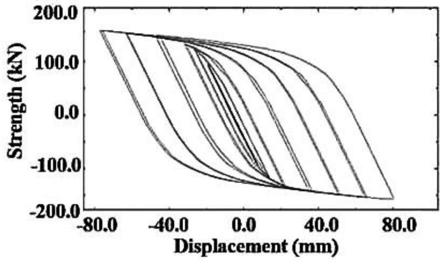


(b)

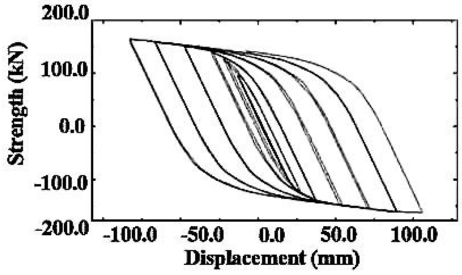
Figure 14. Investigating the effect of the proposed damper width and the number of TADAS on energy dissipation of studied frames **a.** Damper with 5 mm thickness **b** Damper with 10 mm thickness



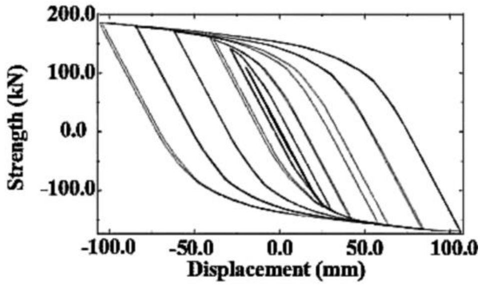
No Damper



W:50 6D t:5



W:75 6D t:5



W:100 6D t:5

Figure 15. Hysteresis loops for a number of studied frames

TABLE 4. Comparisons of dissipation energy for the simulated frames

Contraction	Dissipation energy (kN.m)	Normalized dissipation energy with respect to no damper case
No Damper	39	1.00
W:50 2D t:5	57	1.46
W:50 4D t:5	66	1.69
W:50 6D t:5	94	2.41
W:50 2D t:10	55	1.41
W:50 4D t:10	63	1.62
W:50 6D t:10	90	2.31
W:75 2D t:5	83	2.13
W:75 4D t:5	104	2.67
W:75 6D t:5	144	3.69
W:75 2D t:10	79	2.03
W:75 4D t:10	99	2.54
W:75 6D t:10	139	3.56
W:100 2D t:5	79	2.03
W:100 4D t:5	99	2.54
W:100 6D t:5	111	2.85
W:100 2D t:10	76	1.95
W:100 4D t:10	94	2.41
W:100 6D t:10	105	2.69

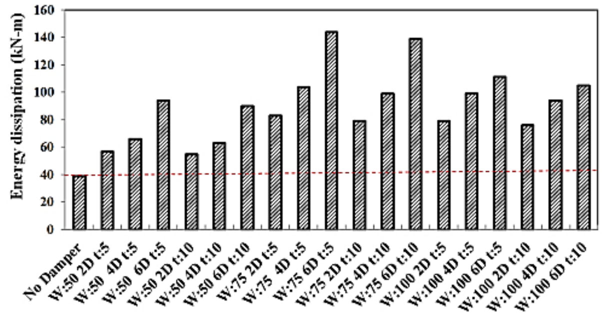


Figure 16. Comparisons of dissipation energy for the simulated frames

As can be seen in Figure 17, for both thicknesses considered for TADAS, the use of a curved damper with a width of 75 mm has the best performance in terms of energy dissipation.

5. 2. Strength The values of the frame strengths are compared with each other in Table 5 and Figure 16. As it is seen, the use of curved-TADAS steel dampers in the frames examined has increased the frame strength by 1.25 to 2.3 times relative to the non-dampening mode depending on the geometric characteristics and the number of TADAS. In other words, the nonlinear deformation of the proposed damper has led to an increase in energy absorption of the frames and thereby the frames can show more resistance.

Adding curved-TADAS steel damper to the frames and transferring the force to it, leads to yield during the earthquake. Thus, a large amount of input energy of the structure is dissipated. One of the reasons for using this type of damper is that in designs usually, it is attempted to destroy the damper instead of the structure so that after the earthquake it can be replaced.

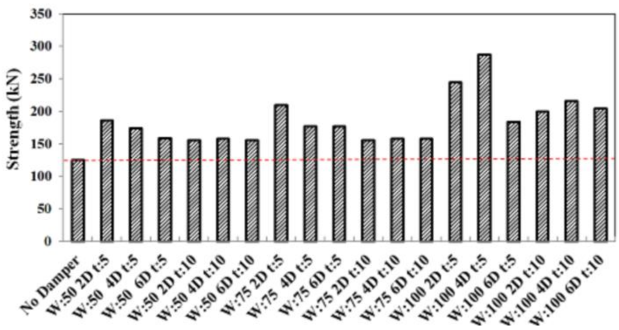


Figure 17. Comparisons of strength for the simulated frames

TABLE 5. Strength of the investigated frames

Contraction	Strength (kN)	Normalized strength with respect to No damper case
No Damper	125	1.00
W:50 2D t:5	186	1.49
W:50 4D t:5	174	1.39
W:50 6D t:5	159	1.27
W:50 2D t:10	156	1.25
W:50 4D t:10	158	1.26
W:50 6D t:10	156	1.25
W:75 2D t:5	210	1.68
W:75 4D t:5	177	1.42
W:75 6D t:5	177	1.42
W:75 2D t:10	156	1.25
W:75 4D t:10	158	1.26
W:75 6D t:10	158	1.26
W:100 2D t:5	245	1.96
W:100 4D t:5	287	2.30
W:100 6D t:5	184	1.47
W:100 2D t:10	200	1.60
W:100 4D t:10	216	1.73
W:100 6D t:10	204	1.63

5. 3. Hysteresis Damping Ratio

The structures are able to undergo nonlinear deformations under severe earthquake loading and deplete energy by their ductility and prevent destruction. Ductility describes the extent to which a structure can undergo large deformations without failing [33].

The Hysteresis energy means deprecating energy by nonlinear deformation loops and is shown by the area of force-deformation curves (hysteresis curve). Structures have a low energy dissipation capacity. The hysteresis damping or energy dissipation per cycle is expressed by A_h area as shown in Figure 18. The equivalent viscosity damping ratio for this area is equal to [33]:

$$\xi_{eq} = \frac{A_h}{2\pi V_m \Delta_m} = \frac{A_h}{4\pi A_e} \quad (1)$$

V_m represents the mean of maximum tensile and compressive forces, Δ_m represents the mean of maximum displacement of tensile and compressive forces in each cyclic loading. A_e is the area of energy stored in a linear elastic system under static and effective stiffness conditions with $K_{eff} = V_m/\Delta_m$. Also, the area of dissipated energy in each cycle (A_h) is equal to the area of the rectangle whose side is equal to the

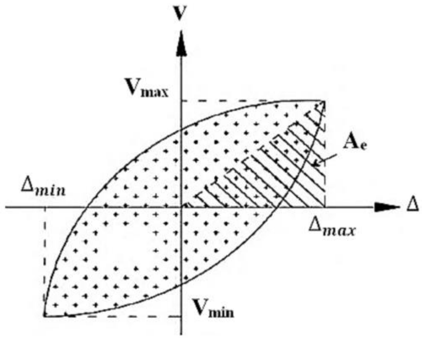


Figure 18. The force-displacement curve for equivalent hysteresis damping [33]

total compressive forces in the structure (2Vm), and the other side is equal to the sum of the maximum structural displacement (2Δm). So, A_h=4VmΔm [33].

Hysteresis damping ratio for the simulated frames is shown in Figure 19. The proposed damper has increased the hysteresis damping ratio by 6 times compared with non-damper mode. Since, after the earthquake, all members remain elastic, it is possible to reuse the structure only by replacing the damper, which completely reflects the cost-effectiveness of using these parts for seismic design of new steel buildings and the improvement of existing buildings against earthquakes.

The effect of the width of curved damper on hysteresis damping ratio of SMRF has been investigated in Figure 20. As it is shown, when the thickness of the TADAS damper is less, the curved damper, with a smaller width, has a higher hysteresis damping ratio.

Figure 20 shows that the increase in TADAS plates can enhance the hysteresis damping ratio; so that the TADAS damper with 6 plates has a much better damping ratio than a TADAS damper with 2 plates. So, the use of the TADAS system, along with a curved damper with more energy absorption, improves the seismic performance of MRSF. In dampers with the same number, with a decrease in thickness, the hysteresis damping ratio increases and the damper performance improves.

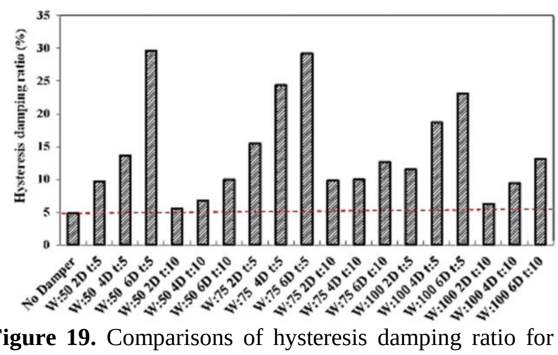


Figure 19. Comparisons of hysteresis damping ratio for the simulated frames

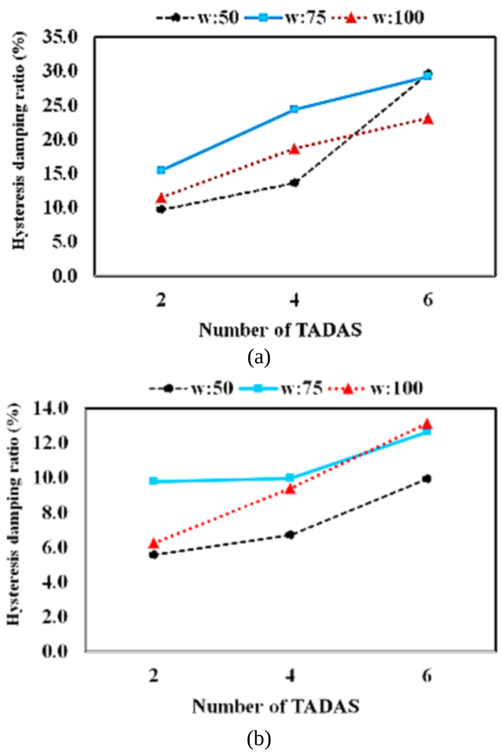


Figure 20. Investigating the effect of damper thickness and width parameters on hysteresis damping ratio of studied frames (**a**) Damper with 5 mm thickness (**b**) Damper with 10 mm thickness

5. 4. Effective Stiffness Figure 21 shows the effective stiffness of all the frames. As can be seen, curved-TADAS dampers can increase the stiffness of the frames by 4.12 times depending on thickness and the number of TADAS. Thickness selection of the TADAS damper has a considerable effect on the frame stiffness; so that a lower thickness damper has a better performance and has been able to significantly increase the effective stiffness of the frame. Therefore, it is concluded that the thickness of the TADAS plates should not be considered excessively.

Rigid connections due to the low plastic rotational capacity are affected by severe earthquakes and are damaged due to the failure of the entire structure. In order to prevent the fracture of the joints and breakdowns of the members of the main structures, curved-TADAS dampers have been used at the beam-to-column connection. As mentioned, the application of the proposed damper in seismic vibrations control of MRSF cause inelastic deformations to be concentrated on damper and the damages of the main structure reduce.

5. 5. Ductility Ductility is important parameter which shows the ability of structure to accept deformations in the plastic range, without significantly

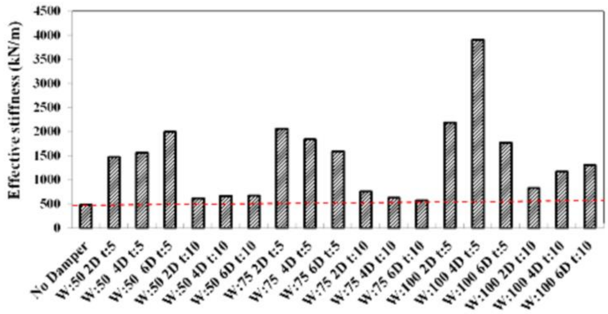


Figure 21. Comparisons of effective stiffness

altering the strength. The ductility ratio is defined as the maximum displacement divided by yield displacement. The yield displacement is equal to the displacement in the starting point of the nonlinear behavior of load-displacement curve. The ductility ratios for the 19 simulated models are shown in Figure 22. The use of curved-TADAS damper has improved the ductility of all examined frames. The maximum and minimum amount of increase in ductility is equal to 14 and 287% respectively, which corresponds to W:50 4D t:10 and W:75 6D t:5 states. According to Figure 22 curved-TADAS dampers due to suitable ductility and inelastic deformation in steel plates (blades) increase the frame damping considerably and reduce the seismic demand.

6. COMPARISON OF THE PROPOSED DAMPER WITH CURVED DAMPER

After evaluating the performance of the curved-TADAS dampers, in this section, the performance of these dampers is compared with the curved dampers. The most optimal damper was selected from the 19 investigated modes and simulated without TADAS damper (only in a curved form) and the responses were compared. For this purpose, the stiffness of both type of damper was calculated using theoretical relationships. The stiffness of TADAS damper is calculated using Equation (2). This equation presented by Tsai et al. [34]. Also, the equivalent stiffness of the proposed damper is calculated using the parallel spring law [28] according

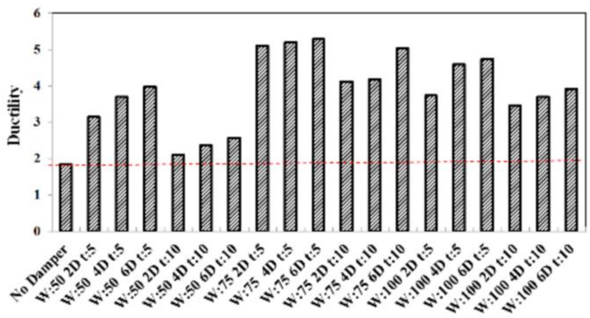


Figure 22. Comparisons of ductility

to Equations (3) to (7) (Figures 23 and 24). Since the stiffness obtained from the mentioned equations for the two dampers are approximately close to each other, so comparison between them can be an adequate comparison. The W:75 6D t:5 mode has the best performance according to energy dissipation, strength, ductility and hysteresis damping ratio. In Table 6, outputs from the hysteresis curve are presented for 3 different modes. In this table, the percentage increase of each output is given in brackets. Also, in Figure 25, load-displacement hysteretic curves of frames equipped with curved-TADAS damper are compared with each other.

After calculating the stiffness values of the two types of damper according to Equations (2) to (7), the equivalent stiffness of the combined damper was about 11% higher than the stiffness values of the TADAS damper. On the other hand, the energy absorption by combined damper is 37% higher than that of the TADAS dampers. As it is seen, both types of used damper have a positive effect and improve the behavior of MRSF against hysteresis loads. On the other hand, comparison of curved-TADAS with curved dampers shows that curved-TADAS dampers have a better performance than curved dampers. These dampers have a high degree of stiffness and improve the stiffness and damping of the frames. Frames that only have a curved damper are more damaged due to buckling and lack of sufficient space for deformation compared to curved-TADAS dampers. So, it is possible to use curved-TADAS dampers more confidently in important structures, such as hospitals and schools, as well as in highly sensitive structures, in which earthquakes with low levels and minor damage are harmful to them.

$$K_{TADAS} = \frac{NEbt^3}{6h^3} \tag{2}$$

$$\Delta = \frac{p}{K} \tag{3}$$

$$P = \frac{d^2 t}{6\Delta + d}\sigma \tag{4}$$

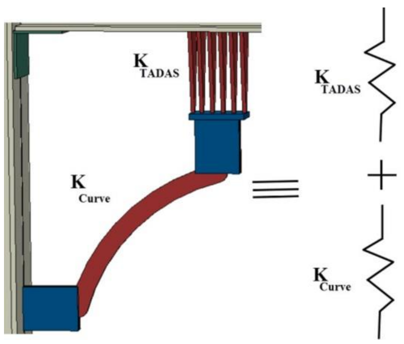


Figure 23. Equivalent stiffness in Curved-TADAS damper

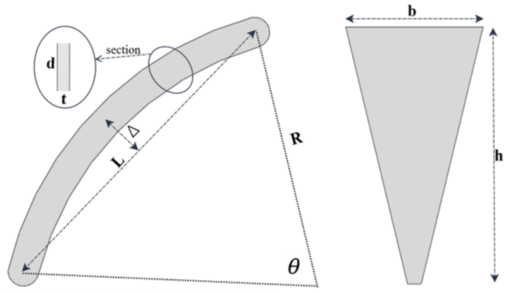


Figure 24. Effective Parameters in stiffness Damper

TABLE 6. Comparison of the proposed damper with curved damper

Damper type	Strength (kN)	Ductility	Energy dissipation (kN.m)	Hysteresis damping ratio (%)
No damper	125	1.84	39	4.8
Curved-TADAS damper	177	5.29	144	29.2
Curved damper	138	3.81	105	25

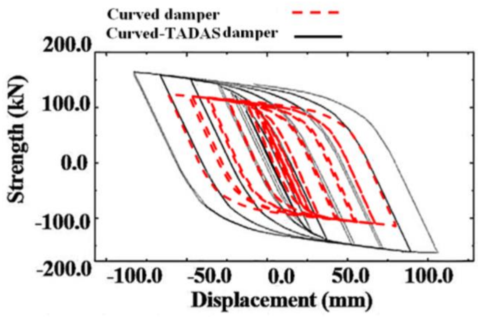


Figure 25. Comparison of hysteresis curves for frames with curved-TADAS damper and frames with curved damper

$$\Delta = \frac{L\left(1-\cos\frac{\theta}{2}\right)}{2\sin\frac{\theta}{2}} \tag{5}$$

$$K_{curve} = \frac{\frac{d^2 t}{6\Delta + d}\sigma}{\frac{L\left(1-\cos\frac{\theta}{2}\right)}{2\sin\frac{\theta}{2}}} \tag{6}$$

$$K_{curve-TADS} = \frac{K_{TADAS} \times K_{curve}}{K_{TADAS} + K_{curve}} \tag{7}$$

Which N is the number of triangular plates, E is the Young's modulus, b is the base width of damper, t is the plate thickness, h and σ are the height of triangular and yielding stress in damper, respectively.

7. CONCLUSIONS

The present study examined the effect of curved-TADAS dampers on the improvement of the seismic behavior of MRSF. For this purpose, FEM was used and the responses of MRSF in the conditions with and without damper against hysteresis loads were investigated. The variables included the thickness and number of TADAS plates and the width of the curved damper. The response of the frames in different modes was compared with parameters such as energy dissipation, strength, stiffness, hysteresis damping ratio, and ductility. At the end, the performance of the proposed dampers was compared with the curved damper. Also, the accuracy of the simulation method was evaluated by simulating two experimental tests that were made in previous studies, and a suitable agreement was observed. The results show that the use of curved-TADAS damper systems reduces the structural responses to seismic loading and prevents structural failure due to the dissipation of considerable amount of seismic input energy. In this method, the damper is mounted at the beam-column connection and absorbs and depletes the energy of the structure during earthquake. The function of these systems is such that, by performing special deformations, they absorb and deplete considerable amount of earthquake input energy of the structure. In other words, the energy input of the earthquake is directed to the beam-column connection location of the structure where the damper is installed, and the damper elements are yielded. The amount of energy received by other members of the structure is reduced due to the yielding of the damper, and less force is applied to them and they do not yield; so the proposed damper can prevent the structural failure.
According to the thickness and number of TADAS plates and the curved damper thickness, the proposed dampers can increase the energy dissipation, hysteresis damping ratio, ductility and the stiffness of the MRSF 3.7, 2.9, 6, and 4.1 times respectively. Also, the comparison of the proposed dampers with the curved dampers showed that curved-TADAS dampers have better performance. For example, ductility and energy dissipation of frame equipped with a curved-TADAS damper has increased by 38 and 37 percent, respectively, compared to curved dampers. The reason for this is that there is more space in the proposed dampers for deformation and energy dissipation, and these dampers greatly increase the energy dissipation of the frames without a significant increase in stiffness. Adding the curved-TADAS damper to the structure and transferring the calculated force to it will cause the damper to yield when the loading takes place and, as a result, depreciates a large amount of input energy into the structure. In fact, in this method, the failure operation does not occur on the structural skeleton and it occurs on the curved-TADAS damper, which can be replaced after loading.

8. REFERENCES

1. Lee, C. H., Jeon, S. W., Kim, J. H., and Uang, C. M. "Effects of panel zone strength and beam web connection method on seismic performance of reduced beam section steel moment connections." ***Journal of Structural Engineering***, Vol. 131, No. 12, (2005), 1854-1865.
2. Ciutina, A. L. and Dubina, D. " Seismic behaviour of steel beam-to-column joints with column web stiffening." ***Steel and Composite structures***, Vol. 6, No. 6, (2006), 493-512.
3. Saravanan, M., Arul, J., Marimuthu, V., and Prabha, P. "Advanced analysis of cyclic behaviour of plane steel frames with semi-rigid connections." ***Steel and Composite Structures***, Vol. 9, No. 4, (2009), 381-395.
4. Hus, H. L., and Tsao, J. W. "Flexural-torsional performance of thin-walled steel hollow box columns subjected to a cyclic eccentric load." ***Thin-Walled structures,*** Vol. 45, No. 2, (2007), 149-58.
5. Chou, C. C., Tsai, K. C., Wang, Y. Y., and Jao, C. K. "Seismic rehabilitation performance of steel side plate moment connections". ***Earthquake Engineering & Structural Dynamics***, Vol. 39, No. 1, (2010), pp. 23-44.
6. Hsu, H. L., and Li, Z. C. " Seismic performance of steel frames with controlled buckling mechanisms in knee braces." ***Journal of Constructional Steel Research***, Vol. 107, (2015), 50-60.
7. Dubina, D. and Stratan, A. "Behaviour of welded connections of moment resisting frames beam-to-column joints." ***Engineering Structures***, Vol. 24, No. 11, (2002), 1431-40.
8. Pucinotti, R. "Cyclic mechanical ,odel of semirigid top and seat and double web angle connections." ***Steel and Composite Structures***, Vol. 6, No. 2, (2006), 139-157.
9. Gerami, M., Saberi, H., Saberi, V., and Daryan, A. S. "Cyclic behavior of bolted connections with different arrangement of bolts." ***Journal of Constructional Steel Research***, Vol. 67, No. 4, (2011), 690-705.
10. Aschheim, M.A."*Moment-resistant structure, sustainer and method of resisting episodic loads*." ***United State Patent***, No 6,012,256, (2000).
11. Daniel, C., Hemalatha, L., Tensing, D. and Sundar Manoharan, S. "Seismic Mitigation of Building Frames using Magnetorheological Damper", ***International Journal of Engineering, Transactions B: Applications***, Vol 32, No. 11, (2019), 1543-1547.
12. Seid, S., Chandramohan, S., Sujatha, S. (2019). "Design and Evaluation of a Magnetorheological Damper Based Prosthetic Knee", ***International Journal of Engineering (IJE), IJE Transactions B: Applications***, Vol. 32, No. 1, 146-152.
13. Polocoser, T.,Leimcke, J., and Kasal, B. "Report on the seismic performance of three-dimensional moment-resisting timber frames with frictional damping in beam-to-column connections." ***Advance in Structural Engineering***, Vol. 21, No.11, (2018), 1652-1663.
14. Tsai, K. C., Hsu, C. H., Li, C. H., and Chin, P. Y. " Experimantal and analytical investigations of steel panel dampers for seismic applications in steel moment frames." ***Earthquake Engineering and Structural Dynamics***, Vol. 47, No. 6, (2018), 1416-1439.
15. El-Bahey, S. and Bruneau, M. "Buckling restrained braces as structural fuses for the seismic retrofit of reinforced concrete bridge bents." ***Engineering Structures***, Vol. 33, No. 3, (2011), 1052-1061.
16. Roeder, C. W., and Popov, E. P. "*Inelastic behavior of eccentrically braced steel frames under cyclic loadings*." NASA STI/Recon Technical Report, (1997).

17. Chen, Y. T. and Chai, Y. H. “Effect of brace stiffness on performance of structures with supplemental maxwell model-based brace-damper systems.” ***Earthquake Engineering and Structural Dynamics***, Vol. 40, No. 1, (2011), 75-92.
18. Benavent-Climent, Amadeo. “A brace-type seismic damper based on yielding the walls of hollow structural sections.” ***Engineering Structures***, Vol. 32, No. 4, (2010), 1113-22.
19. Kang, J. D., and Tagawa, H. “Seismic performance of steel structures with seesaw energy dissipation system using fluid viscous dampers.” ***Engineering Structures***, Vol. 56, (2013), 431-442.
20. Piedrafita, D., Cahis, X., Simon, E., and Comas, J. “ A new modular buckling restrained brace for seismic resistant buildings.” ***Engineering Structures***, Vol. 56, (2013), 1967-1975.
21. Oh, K., Lee, K., Chen, L., Hong, S. B., and Yang, Y. “Seismic performance evaluation of weak axis column-tree moment connections with reduced beam section.” ***Journal of Constructional Steel Research***, Vol. 105, (2015), 28-38.
22. TahamouliRoudsari, M., Eslamimanesh, M. B., Entezari, A. R., Noori, O., and Torkaman, M. “Experimental Assessment of Retrofitting RC Moment Resisting Frames with ADAS and TADAS Yielding Dampers”. ***Structures,*** Vol. 14, (2018), 75-87.
23. Ghaffary, A., & Karami Mohammadi, R. “Framework for virtual hybrid simulation of TADAS frames using opensees and abaqus”, ***Journal of Vibration and Control***, Vol. 24, No. 11, (2018), 2165-2179.
24. Farsangi, E. N., Tasnimi, A. A., Yang, T. Y., Takewaki, I., and Mohammadhasani, M. “Seismic performance of a resilient low-damage base isolation system under combined vertical and horizontal excitations”, ***Smart Structures and Systems,*** Vol. 22, No. 4, (2018), 383-397.
25. Garivani, S., Aghakouchak, A. A., and Shahbeyk, S. “Seismic Behavior of Steel Frames Equipped with Comb-Teeth Metallic Yielding Dampers”. ***International Journal of Steel Structures***, Vol. 19, No. 4, (2019), 1070-1083.
26. Saghafi, M. H., & Golafshar, A. L. I. “Analytical assessment of reinforced concrete frames equipped with TADAS dampers”. ***Journal of Rehabilitation in Civil Engineering***, Vol. 7, No. 2, (2019), 302-317.
27. Palermo, M., Silvestri, S., Gasparini, G., and Trombetti, T. (2015). “Crescent shaped braces for the seismic design of building structures.” ***Materials and Structures***, Vol. 48, No. 5, (2015), 1485-1502.
28. Hsu, H. L., and Halim, H. “Improving seismic performance of framed structures with steel curved dampers.” ***Engineering Structures***, Vol. 130, (2017), 99-111.
29. Hibbitt, H., Karlsson, B., and Sorensen, E. “ABAQUS user’s manual.” Providence, RI: Dassaulat Systems Simulia Crop, (2016).
30. ATC-24,“Guidelines for Cyclic Seismic Testing of Components of Steel Structures for Buildings,” Report No. ATC-24, ***Applied Technology Council***, Redwood City, CA. (1992).
31. Pourasil, M.B., Mohammadi, Y., and Gholizad, A. “ A proposed procedure for progressive collapse analysis of common steel building structures to blast loading.” ***KSCE Journal of Civil Engineering***, Vol. 21, No. 6, (2017), 2186-2194.
32. Oh, S. H., Kim, Y. J., and Ryu, H. S. Seismic performance of steel structures with slit dampers. ***Engineering Structures***, Vol. 31, No. 9, (2009), 1997-2008.
33. Priestley, M.N., Seible, F. and Calvi, G.M., Seismic design and retrofit of bridges. John Wiley & Sons, (1996).
34. Tsai, K. C., Chen, H. W., Hong, C. P., and Su, Y. F. (1993). Design of steel triangular plate energy absorbers for seismic-resistant construction. ***Earthquake Spectra***, Vol. 9, No. 3, (1993), 505-528.

Performance Evaluation of Curved-TADAS Damper on Seismic Response of Moment Resisting Steel Frame

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P A P E R I N F O

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چکیده

در مطالعه حاضر عملکرد میراگرهای ترکیبی منحنی و میراگرهای مثلثی افزاینده میرایی و سختی (TADAS) در قاب خمشی فولادی مورد بررسی قرار گرفت. این دمپرها از نوع فعال بوده و در ناحیه اتصال تیر به ستون نصب می‌شوند. پارامترهای مورد بررسی به ترتیب شامل عرض دمپر منحنی (۵۰، ۷۵ و ۱۰۰ میلیمتر)، ضخامت دمپر TADAS (۵ و ۱۰ میلیمتر) و تعداد میراگرهای TADAS (۲، ٤ و ٦) می‌باشند. ارزیابی قاب‌های خمشی فولادی با استفاده از روش اجزاء محدود و به کمک نرم افزار ABAQUS انجام شد. دو مطالعه آزمایشگاهی مختلف به منظور ارزیابی صحت روش شبیه سازی مورد بررسی، استفاده شد و تطابق مناسبی مشاهده گردید. پاسخ قاب‌ها در حالت‌های مختلف با استفاده از پارامترهایی نظیر استهلاک انرژی، مقاومت، سختی، ضریب میرایی هیسترزیس و شکل پذیری با یکدیگر مورد مقایسه قرار گرفت. در انتها، عملکرد دمپرهای پیشنهادی با دمپر منحنی شکل مورد مقایسه قرار گرفت. نتایج حاصل نشان می‌دهد میراگرهای ترکیبیِ منحنی و TADAS انرژی ورودی لرزه‌ای را به طور قابل توجهی کاهش می‌دهند و از خرابی سازه جلوگیری می‌کنند. عملکرد این دمپرها به گونه‌ای می‌باشد که با تغییرشکل‌های ویژه منجر به استهلاک و جذب انرژی مقدار زیادی انرژی ورودی زلزله به سازه می‌شوند.

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