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JOURNAL OF CIVIL ENGINEERING RESEARCHERS

Seismic Performance Evaluation of Friction Damper and Yielding Metallic Damper in Steel Frame

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Journals-Researchers use only: Received date: 2023.04.21; revised date: 2023.06.10; accepted date: 2023.06.19

Abstract

In recent decades, various control systems have been studied to reduce the vibrations of structures under dynamic forces. Generally, types of structural control systems are classified into energy dissipation systems and seismic isolation systems. Examples of energy dissipation systems include metallic yielding dampers, friction dampers, viscoelastic dampers, viscous dampers, tunable mass dampers, and tunable liquid dampers. This article investigates the seismic performance of friction dampers and metallic yielding dampers in steel frames, as well as the performance of a two-story steel frame strengthened with metallic yielding dampers and combined with friction dampers. For this purpose, five two-story steel frames with eight-story divergent braces were examined: a frame without a damper, a two-story frame with metallic yielding dampers, a two-story frame with friction dampers, a two-story frame with the first floor having friction dampers and the second floor having metallic yielding dampers, and a two-story frame with the first floor having metallic yielding dampers and the second floor having friction dampers. The results show that the use of dampers increases the energy dissipation of the structure and reduces the maximum displacements induced in the structure as well as the base shear. The effect of metallic yielding dampers on reducing the base shear is greater than that of friction dampers, while the effect of friction dampers on increasing energy dissipation and reducing displacements induced in the structure is greater compared to metallic yielding dampers. (DOI:**https//doi.org/10.52547/JCER.5.3.1**)

Keywords: Yielding metallic damper; Friction damper; Energy dissipation; Displacement; Base shear

1. Introduction

An earthquake is an unpredictable event that can occur at different times and intensities, destroying structures. Therefore, retrofitting structures against this phenomenon is inevitable. Usually, moderate earthquakes do not significantly affect the integrity of existing structures, while strong earthquakes reveal their strengths and weaknesses. Earthquakes such as the Northridge earthquake in the United States (1994) and the Kobe earthquake in Japan (1995) have had a significant impact on changing seismic codes and design methods for earthquake-resistant structures [1].

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Conventional structures absorb seismic energy by yielding or fracturing building materials. For example, when beams and columns create plastic hinges, or when concrete structures develop cracks or non-ductile components reach the failure stage, energy absorption occurs. Dampers provide a solution for yielding or dissipating energy, which is a method of absorbing seismic energy. These devices can absorb the majority of earthquake energy and keep the structure intact and ready for immediate use after an event [2].

In recent decades, various control systems have been studied to reduce structural vibrations caused by dynamic forces. Generally, types of structural control systems are divided into two categories: energy dissipating and seismic isolation systems. Examples of energy-dissipating systems include metallic dampers (yielding), friction dampers, viscoelastic dampers, viscous dampers, tuned mass dampers, and liquid dampers [3].

In general, seismic control systems are classified into four types: passive, active, semi-active, and hybrid control systems [3]. Devices that do not require external energy to function are called passive control devices. These systems are more reliable because they continue to work even if the energy source, which is likely to be interrupted during an earthquake, is cut off. Since these devices are located inside the structure and do not have an external energy source, they never change the internal energy of the structure and are incapable of destabilizing the structure [4, 5]. However, most passive control devices, such as friction sliding, yielding of metal, and deformation in viscoelastic bodies or fluids, work after a certain stage and can be designed not to be active in low lateral forces [6]. Yielding dampers and friction dampers are among the passive control systems.

Multiple research studies have been conducted on the application of various types of dampers in different structures. Mirzaifi and colleagues [7] concluded in their research that friction dampers introduce a counter-directional force to the structural movement, opposing the motion of the building and dissipating a considerable amount of input energy. Khaleghiyan and Tehranizadeh [8] demonstrated in their studies that friction dampers have a special capability in reducing the seismic energy of a structure. Bayat et al. [9] showed that the use of friction dampers increases the ductility of a structure. Karami and Sarmast [10], as well as Papadopoulos et al. [11], demonstrated that friction devices significantly improve the seismic resistance and damage control potential of braced and skeletal structures. Amiri [12] demonstrated in their research that properly distributed friction dampers can effectively control lateral displacement and diaphragm rotation. Latorre et al. [13], Manatori et al. [14], and Moneer et al. [15] concluded in their analyses that adding friction dampers to moment frames reduces the displacement by approximately 15%.

Kamasi et al. [16] investigated the effect of using steel-yielding dampers on the behaviour of structures and found that shape-adaptive structures equipped with steel-yielding dampers exhibit greater ductility and less displacement. Vada et al. [17] showed that steel-yielding dampers exhibit stable hysteretic behaviour and gradually increase the stiffness of the structure, improving its capacity to absorb energy. Li et al. [18] and Chan et al. [19] demonstrated that the use of steel-yielding dampers significantly increases the ultimate energy absorption capacity of the structure. Oh et al. [20] showed that increasing the length of the damper enhances the connection strength in skeletal structures. Their investigations also revealed that energy dissipation and plastic deformation are concentrated in the yielding dampers, preventing the non-elastic behaviour of beams and columns. Khoshnoodian and Kiani [21] found that adding a certain number of dampers to each floor effectively improves the structural response, but exceeding that number has no significant effect on the structural response improvement. Tohidi Moghadam and Saeed Monir [22] investigated a new type of circular-shaped yielding dampers and demonstrated that using these dampers in a concentrically braced frame system yields better performance compared to the beam-to-column connection, resulting in a noticeable reduction in displacement and base shear. Safari et al. [23] proposed new samples of yielding dampers for improving the ductility of moment connections and conducted an extensive investigation on them.

In this project, the seismic performance of friction dampers, yielding metal dampers, and their combination in a steel frame, as well as the performance of a two-story steel frame with yielding metal dampers, friction dampers, and their combination, will be analyzed. The ultimate goal of the project is to examine the effects of using yielding metal dampers, friction dampers, and their combination in a two-story steel frame on the maximum lateral displacement, base shear, and energy dissipation of the structure.

2. Friction Dampers

Friction is used as an agent for energy dissipation. Mechanical engineers have long utilized this mechanism to dissipate the kinetic energy of moving bodies. Friction brakes are an example of friction application in the industry. The application of friction in structural engineering has led to the development of friction dampers, which absorb a significant amount of input energy from earthquakes and other dynamic excitations [24]. These types of dampers work based on the friction mechanism between solid bodies. Friction is an excellent energy dissipation mechanism and has been widely and successfully employed for dissipating kinetic energy. Various materials have been used for sliding surfaces. Examples include brake layers on steel, steel on steel, steel on bronze, and bolted connections with graphite combined with stainless steel and other metallic alloys. The choice of base metal for friction dampers is crucial. Corrosion can often reduce the assumed coefficient of friction for the desired service life. In reality, stainless steel alloys corrode and passivate, and their interfacial properties change over time, while bronze and brass increase the rate of corrosion when in contact with low-carbon alloys. In comparison, stainless steel does not show additional concerning corrosion when in contact with bronze, making it suitable for use in friction dampers. Friction dampers have very good performance characteristics. Their response is independent of frequency range and the number of independent loading cycles, thus offering a high potential benefit-to-cost ratio. These dampers fall into the category of hysteretic dampers. They dissipate energy through displacement and self-sliding [5]. All existing friction dampers essentially operate in the same way. One part remains stationary, while the other part dynamically slides on it. Slipping occurs at a certain level of force and moves according to Coulomb's friction law. No motion occurs until a specific force threshold is reached. However, after that, the sliding surface and motion begin. The combination and arrangement of these sliding surfaces create different types of friction dampers, including more complex configurations such as the Pall friction damper [24].

3. Yielding Metal Dampers

By understanding the crystal structure of various metals, we can examine the behaviour of metal yielding under cyclic loading conditions and observe desirable damping properties within the range before the yield point. By shaping a piece of metal into a form that exhibits yielding behaviour under dynamic structural loading (often in the form of an isosceles triangle) and placing it at the connection points between structural members, we can effectively utilize this property for energy dissipation and scattering during earthquakes. The material selection, shape, and placement of these types of dampers should be such that their damping properties are not significantly affected by various influencing factors over the lifetime of the structure. The metal used for constructing such dampers usually needs to exhibit suitable hysteresis behaviour, high fatigue endurance, relative strength, and minimal sensitivity to temperature changes. Essentially, metal dampers rely on the elastic deformation of the metal and the damping resulting from internal friction within the crystals. Various energy absorption systems can be used for this purpose. Yielding dampers are metallic devices that can dissipate energy in an earthquake through non-elastic deformations of the metals. These dampers typically yield in flexural, torsional, axial, or shear modes. They fall into the category of passive dampers in structures and contribute to increased damping and stiffness [2].

4. Analytical Modeling Compatibility Investigation Using Abaqus Finite Element Software

The modelling and validation of a yielding metal damper in Abaqus software were conducted for a laboratory specimen created by Lee et al. (2002) [18]. Abaqus is a unitless finite element software that does not have default or changeable units. The units of different quantities are determined based on the input values of the program [26].

The element used for modelling the investigated shape memory yielding damper in this section is of the Solid type. The dimensions of different parts and the loading conditions are considered according to Figures 1 and 2. The geometric specifications of the model are given in Table 1, and the material properties of the steel used are provided in Table 2.

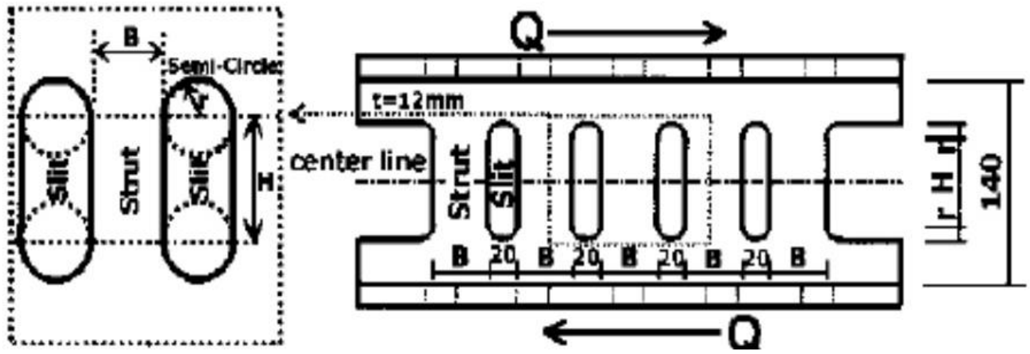

Figure 1: Investigated shape memory yielding metal damper specimen [18]

Table 1:
Geometric specifications of the investigated shape memory-yielding metal damper [18]

H (mm)	B (mm)	t (mm)	n	Case number
80	24	12	7	D0300-2

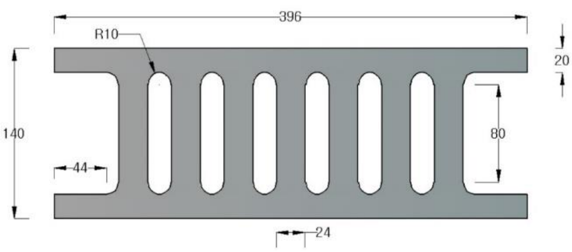

Figure 2: Geometric dimensions of the investigated shape memory-yielding metal damper specimen [18]

Table 2:
Material properties of the steel used in the investigated shape memory-yielding metal damper [18]

Elong (%)	σ_u (MPa)	σ_y (MPa)	υ	ρ (Kg/m3)	E (GPa)
28	451	307	0.3	7850	214

The shape of the elements used is HEX, as shown in Figure 3. For the used Solid element, an 8-node C3D8 mesh type is considered. It should be noted that the mesh size is 10x10 millimetres, resulting in 1380 elements.

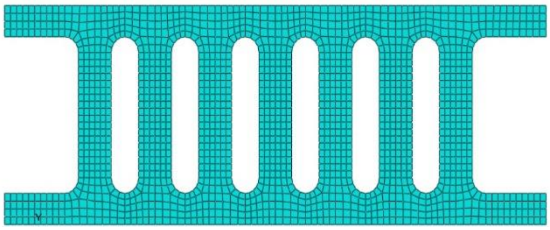

Figure 3: Partitioning and meshing of the investigated model

The bottom surface of the specimen is fully restrained in all directions.

$U_1=0, U_2=0, U_3=0, U_{R1}=0, U_{R2}=0, U_{R3}=0$

The specimen is subjected to only horizontal displacement in the X direction at the reference point with a linear magnitude of 66 millimetres, neglecting the effect of the specimen's weight. Contour plots of the von Mises stress distribution in the investigated specimen after loading and analysis are shown in Figure 4. The force-displacement curve of the numerical model created in Abaqus software and the experimental specimen are compared in Figure 5. The results indicate satisfactory agreement between the numerical and experimental models.

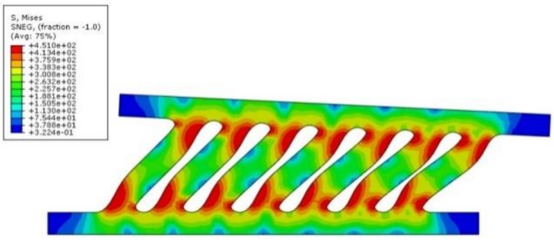

Figure 4: Contour plot of the von Mises stress distribution in the investigated specimen

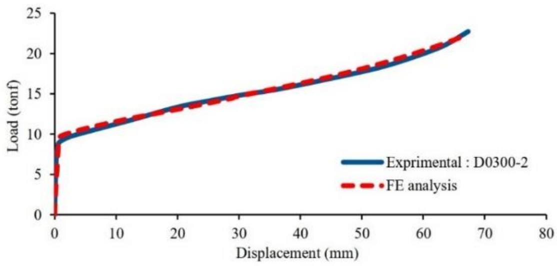

Figure 5: Comparison of the force-displacement curves of the experimental and analytical models

5. Modelling of structures in ETABS software

A two-story building with an eccentrically braced frame system has been designed. In this design, seismic considerations of the building design regulations against earthquakes (Standard 2800) have been taken into account. The design of the mentioned structure was performed using ETABS software. Then, based on the steel sections of beams, columns, and braces, the desired structural frames were simulated to investigate the forces generated in the members and the displacements of the nodes using ABAQUS software. Subsequently, considering the applied loads and their application to the structure, as well as based on the analysis cases, the system response and the desired parameters were determined.

The mentioned steel structures have a uniform plan on all floors, and each floor has an area of 200 square meters. The height of all floors is considered to be 2/3 meters. The lateral load-bearing system of the structure is moment-resisting frames in two orthogonal directions. The connection between beams and columns is simple. All components of the structure are made of St37 steel with ultimate stress of 3700 kg/cm² and yield stress of 2400 kg/cm². The values of live and dead loads for the floors are 200 and 335 kg/m², respectively, and for the roof, they are 150 and 310 kg/m², respectively. The earthquake loads are obtained based on the assumption that the structure is located in seismic zone 4 of Iran. The roofs of the buildings are of block-and-beam type construction, and one-way slab reinforcement is considered. The structural plan and the three-dimensional image of the two-story frame modelled in the ETABS software are shown in Figures 6 and 7, and the results of the structural design are presented in Table 4.

After designing the structure in the ETABS software, a two-span structure with an eccentrically braced frame is selected, and the desired investigations are carried out by modelling it in the Abaqus software. In this study, 5 models with different arrangements have been used, and their specifications are given in Table 5.

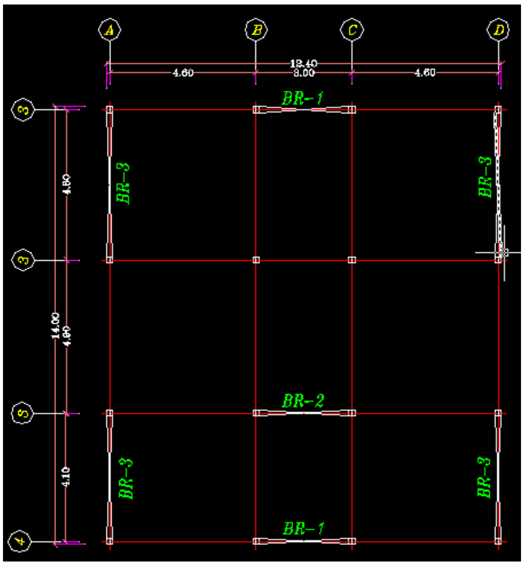

Figure 6: Structural plan under investigation

6. Modelling steps

To create the geometric shape of the members that will be later used for analysis, the Part module is used. Figure 8 shows the image of the modelled frame in the ABAQUS software.

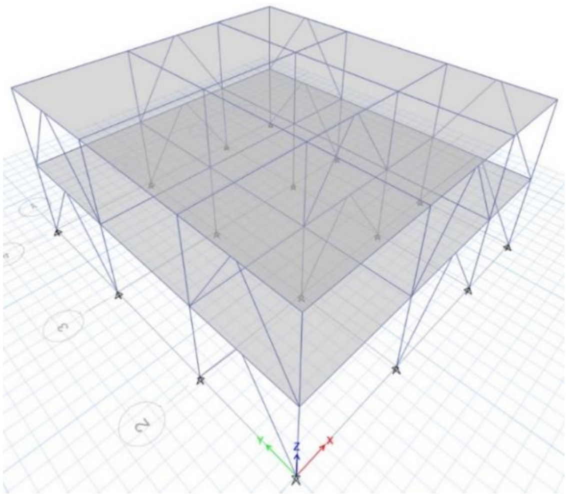

Figure 7: Three-dimensional image of a two-story steel structure with an eccentrically braced frame

Table 3:

Results of the design of the two-story steel structure

Story	Column	Beam	Brace
1	IPB240	IPE240	IPE140
2	IPB240	IPE240	IPE140

Table 4:

Arrangement of braces in the created models

Case No	Number of Stories	Type of Brace	Type of Damper in 1Story	Type of Damper in 1Story	The location of the Brace	Span length of the Damper
SP1	2	EB*	Without Damper	Without Damper	Outside Frames	Without Damper
SP2	2	EB	Metallic yielding Damper	Metallic yielding Damper	Outside Frames	4.8 m
SP3	2	EB	Friction Damper	Friction Damper	Outside Frames	4.8 m
SP4	2	EB	Metallic yielding Damper	Friction Damper	Outside Frames	4.8 m
SP5	2	EB	Friction Damper	metallic yielding damper	Outside Frames	4.8 m

* Eccentrically Brace

The type of analysis considered in this modelling is Dynamic-Explicit analysis. Moreover, Nlgeom is activated in the intended modelling, which means that Abaqus calculates nonlinear geometry. Considering nonlinear geometry in cases where loading on the model results in large displacements is very important [26].

In the software, the weld can be defined as either flexible or rigid, and the interaction between surfaces can be applied based on it. In this study, both pieces are welded to each other using the tie constraint. Since the load must be applied to the centre of the part's surface during loading to avoid creating extra anchors, by defining a reference point at the floor level and constraining this point with multiple MPC constraints, the conditions can be applied.

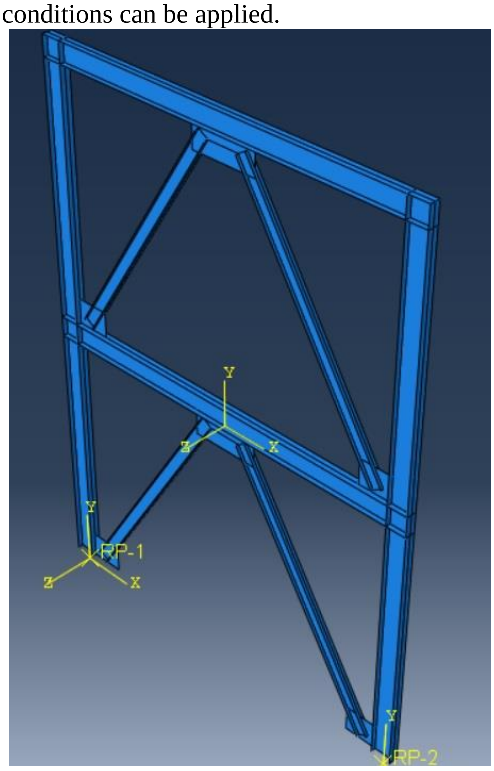

Figure 8: Image of a two-span two-story frame with an eccentrically braced frame modelled in the Abaqus software

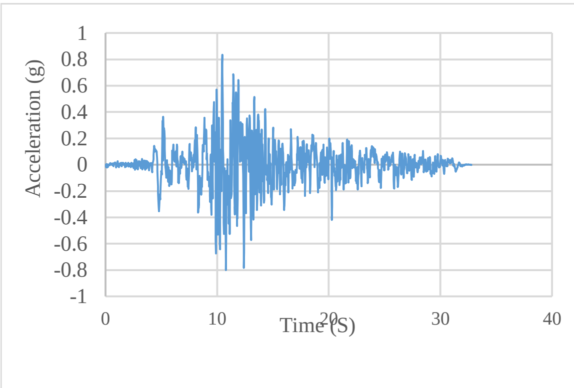

Figure 9: Acceleration mapping of the Tabas earthquake in the X direction

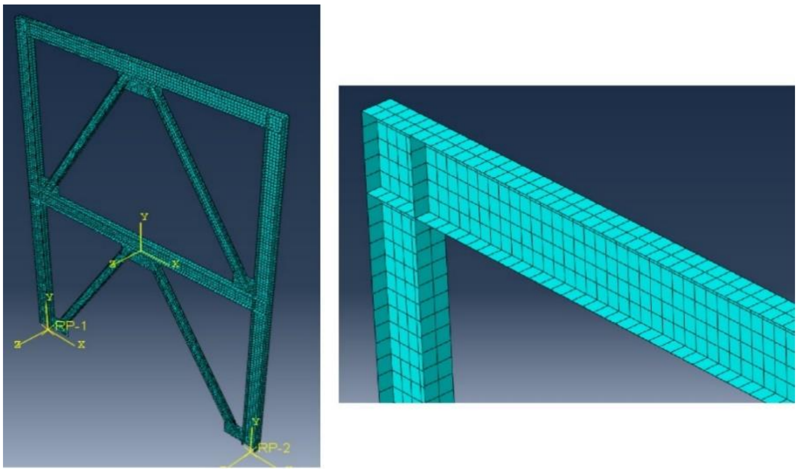

Figure 10: Meshed frame with an eccentrically braced frame

The load applied to the structure is Tabas earthquake. The Tabas earthquake occurs in three directions: X, Y, and Z. The earthquake lasts 33 seconds, but since each earthquake consists of three parts: the initiation, effective, and fading phases, and the greatest impact and damage occur in the time interval of 4 to 20 seconds, therefore, considering that from the 20th second onwards, the acceleration has a negligible value, this time interval is used in the analyses, which reduces the computational time and leads to convergence of the results. Figure 9 shows the acceleration mapping of the Tabas earthquake in the X direction.

Considering the type of analysis and the mentioned explanations, reduced integration with three-dimensional stress family elements (C3D8R) and continuous node type technique have been used for meshing (Figure 10).

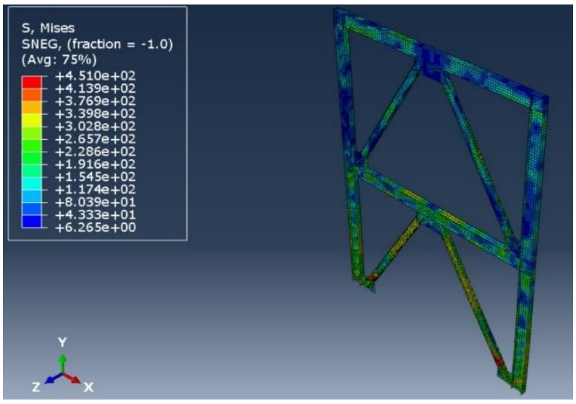

Figure 11: Contour plot of Von Mises stress distribution in the modelled frame in Abaqus software.

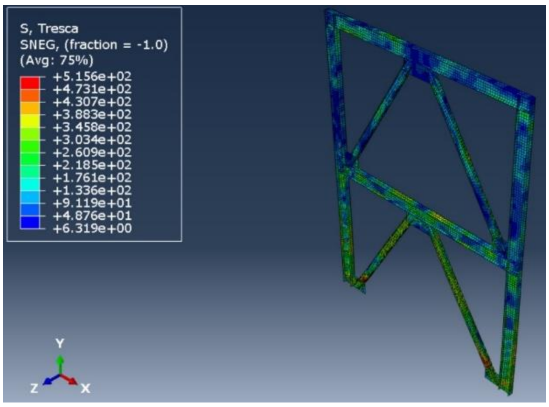

Figure 12: Contour plot of Tresca stress distribution in the modelled frame in Abaqus software.

7. Investigation of the Targeted Frames

As mentioned, five frames (without a brace and with a yielding brace) are examined in this study. The hysteresis curves of each frame are analyzed to evaluate the load-bearing capacity, maximum displacements, and energy absorption and dissipation capabilities of the frames. Figures 11 and 12 depict the contour plots of Von Mises stress and Tresca stress in Frame SP1.

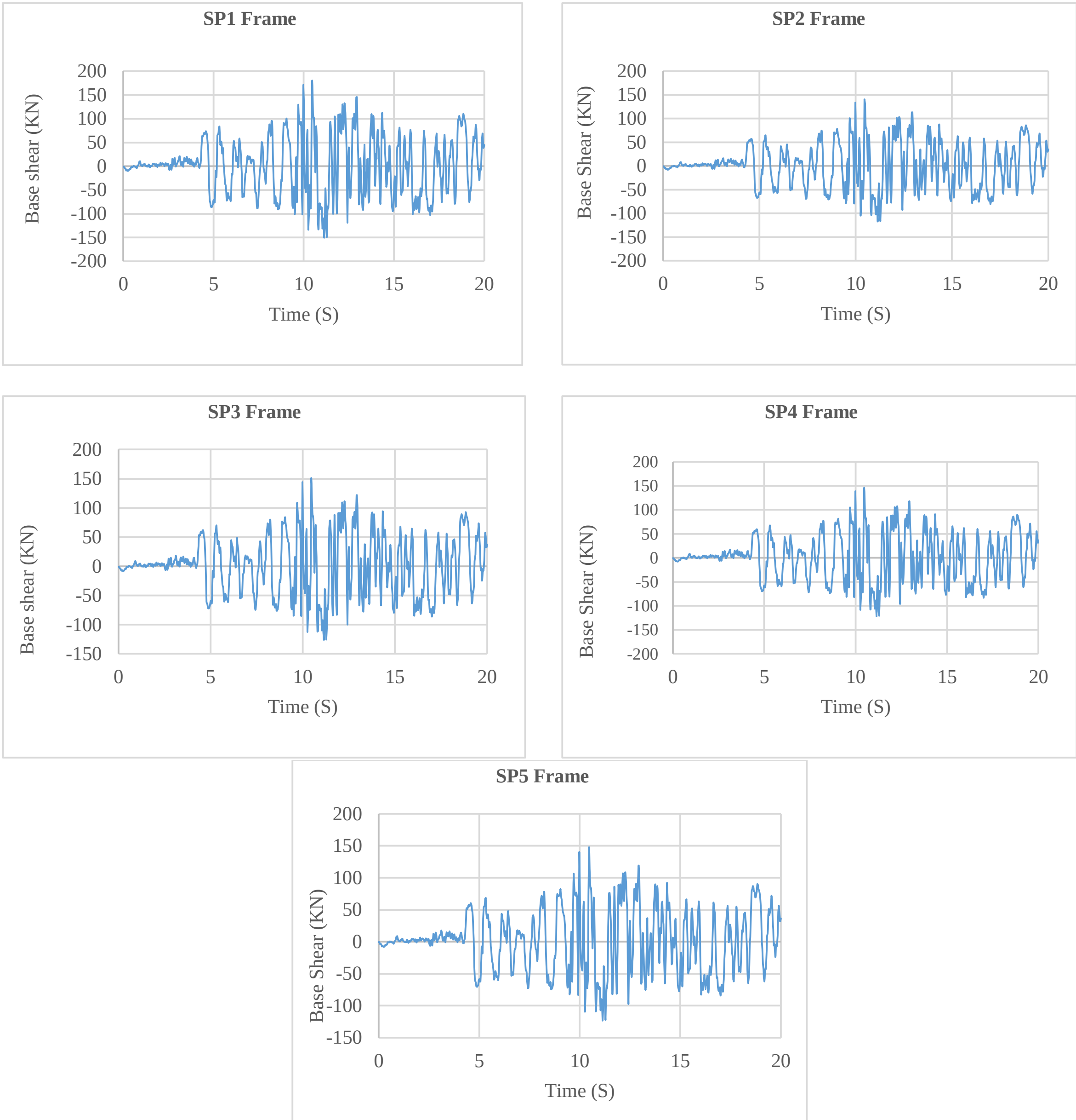

Figure 13: Base shear created in Frames SP1 to SP5

7.1. Investigation of Base Shear in the Examined Frames

The base shear in the braced frames with yielding and friction-based braces is evaluated based on the details provided in Table 5. The results are illustrated in Figure 13 and Table 5.

The examination of the obtained results indicates that the use of yielding braces and friction-based braces reduce the base shear in the investigated frames.

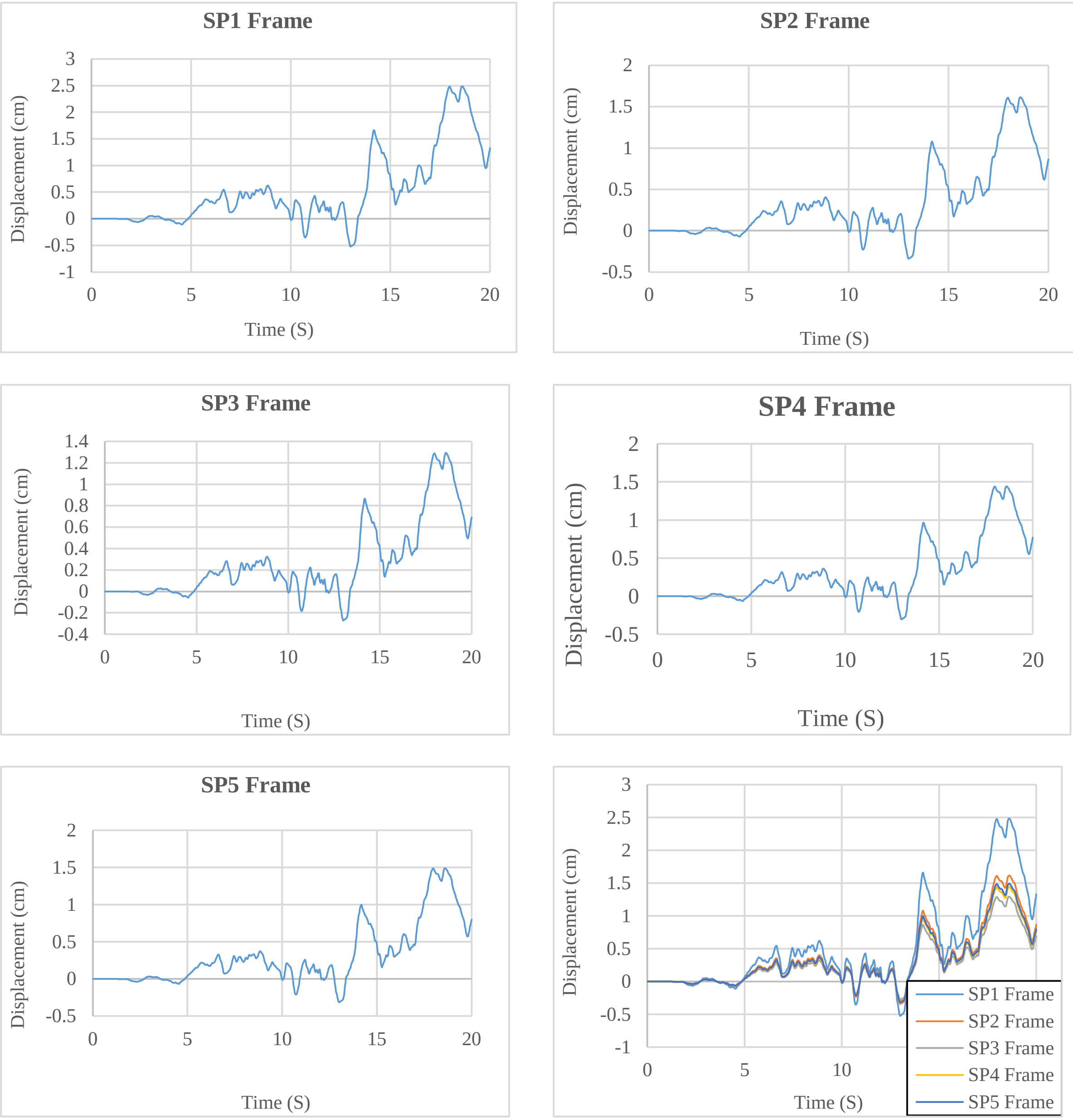

Figure 15: Maximum displacements created in Frames SP1 to SP5

The base shear in the frame where yielding braces are used in both stories is lower compared to the frame with friction-based braces in both stories. Therefore, it can be concluded that the influence of yielding braces on reducing the base shear is greater than friction-based braces. In Frames SP4 and SP5, where a yielding brace is used in one story and a friction-based brace is used in another story, no significant difference is observed in the base shear. The base shear in Frame SP4, which has a yielding brace in the first story and a friction-based brace in the second story, is slightly lower than Frame SP5.

Table 5:
Base shear imposed on the examined braced frames

Case Number	Base Shear (KN)
SP1	180.41
SP2	140.72
SP3	151.54
SP4	146.13
SP5	147.93

7.2. Examination of Maximum Displacements in the Examined Frames

The maximum displacements generated in the braced frames with yielding and friction-based braces are evaluated based on the details provided in Table 5. The results are presented in Figure 15 and Table 6.

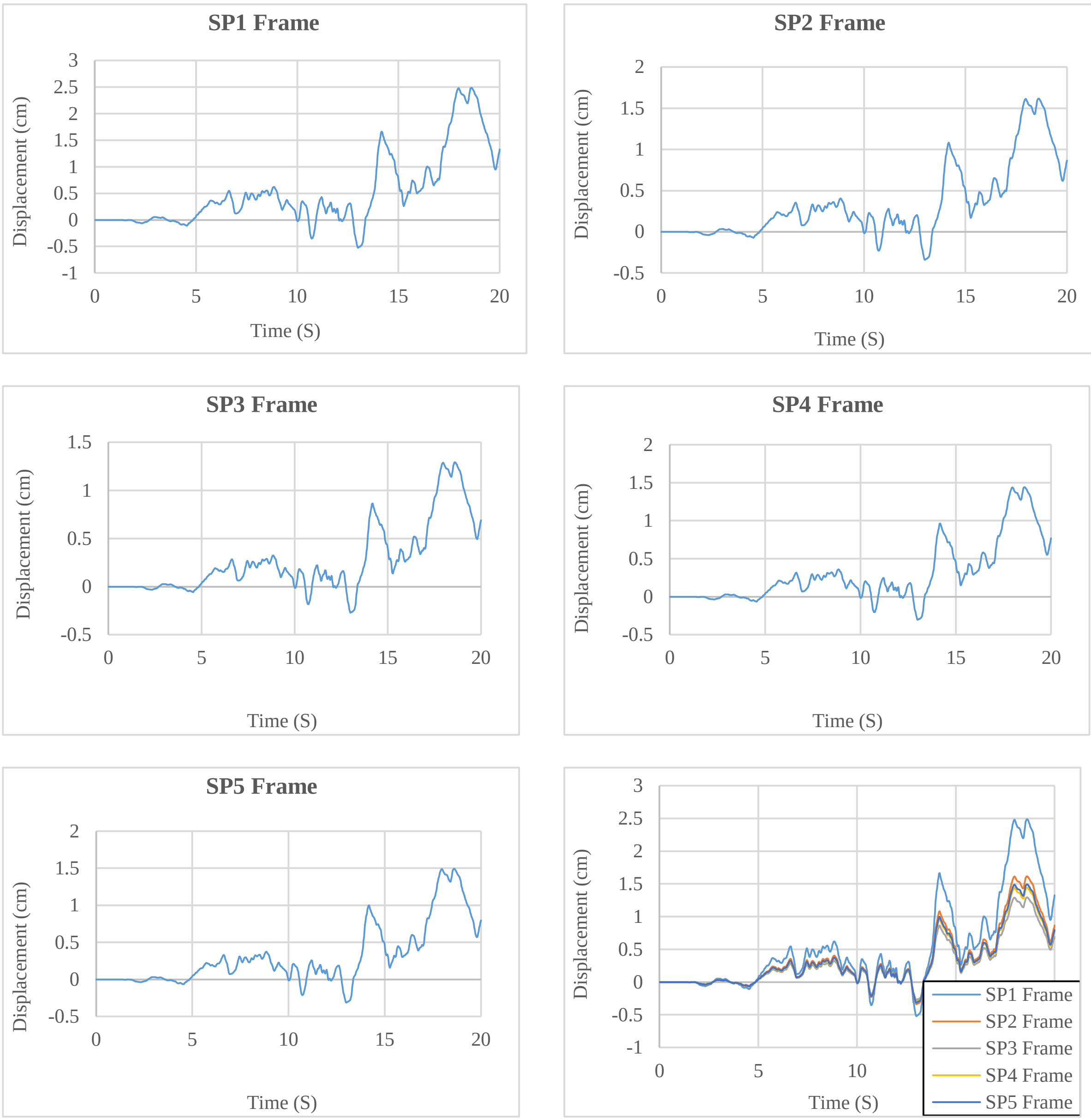

Figure 15: Maximum displacements created in Frames SP1 to SP5

The examination of the obtained results shows that the use of yielding braces and friction-based braces reduce the maximum displacements created in the examined frames. The maximum displacement in the frame where friction-based braces are used in both stories is lower compared to the frame with yielding braces in both stories. Therefore, it can be concluded that the influence of friction-based braces on reducing the maximum displacements created in the structure is greater than yielding braces. In Frames SP4 and SP5, where a yielding brace is used in one story and a friction-based brace is used in another story, no significant difference is observed in the maximum displacements. The maximum displacements in Frame SP4, which has a yielding brace in the first story and a friction-based brace in the second story, are slightly lower than Frame SP5."

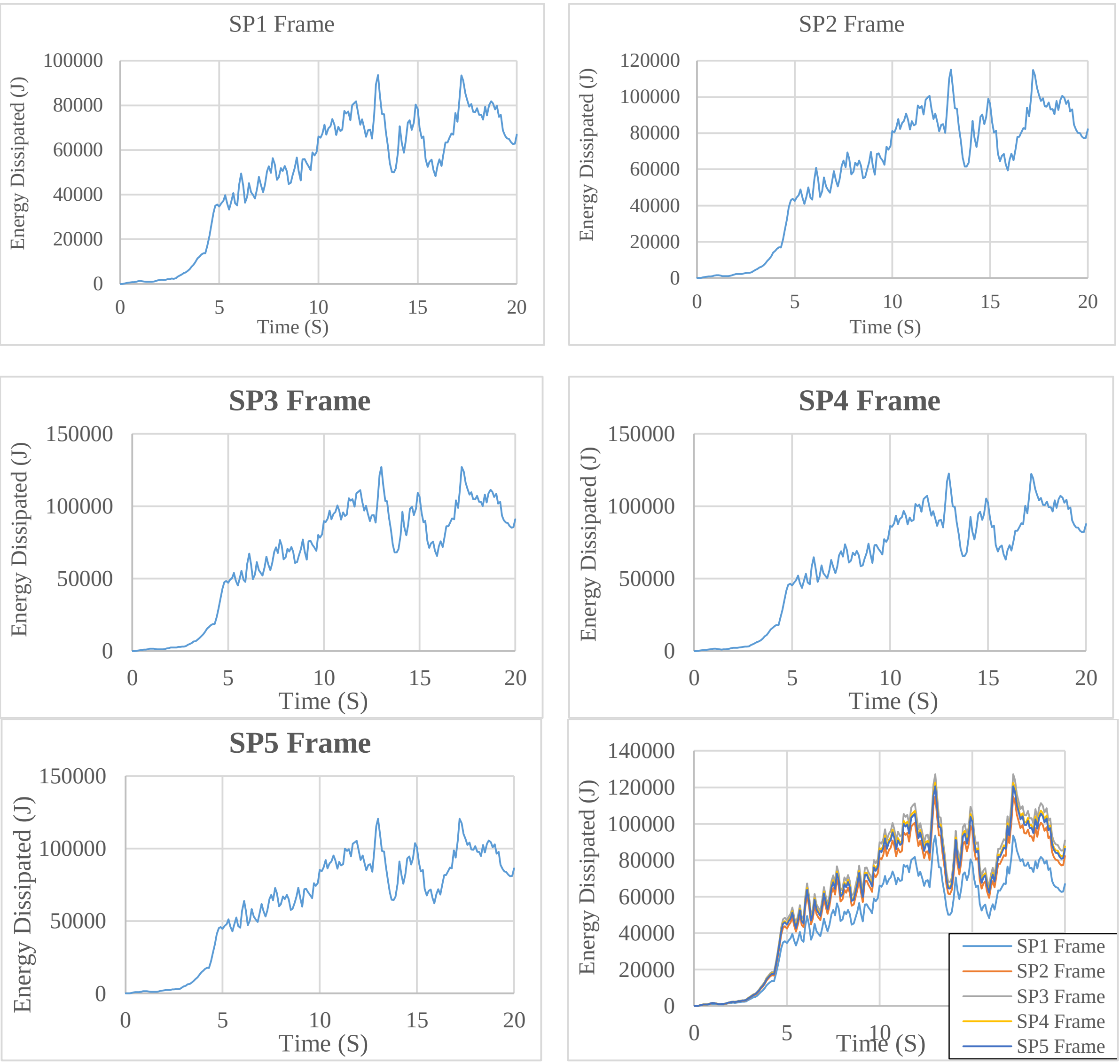

Figure 16: The energy absorption and dissipation capability in Case Numbers

Table 6:
Maximum displacements generated in the examined braced frames

Case Number	Maximum displacement(cm)
SP1	2.48
SP2	1.61
SP3	1.29
SP4	1.44
SP5	1.49

Table 7:
Maximum displacements generated in the studied braced frames.

Case Number	Maximum energy dissipated (J)
SP1	93509.6
SP2	115016.8
SP3	127173.1
SP4	122497.6
SP5	120627.4

7.3. Analysis of Energy Absorption and Dissipation Capability in the Studied Frames

The energy absorption and dissipation capability in frames braced with a divergent brace, in cases without the use of friction damper, and cases using friction and yielding metallic dampers are investigated, as detailed in Table 5, and the results are shown in Figure 16 and Table 7.

The analysis of the obtained results indicates that the use of yielding metallic dampers and friction dampers increases the amount of energy dissipated in the studied frame. The energy dissipated in a frame with friction dampers used in both stories is higher compared to a frame with yielding metallic dampers used in both stories. Therefore, it can be concluded that the influence of friction dampers on increasing the energy dissipated in the structure is higher than yielding metallic dampers.

In SP4 and SP5 frames where a yielding metallic damper is used in one story and a friction damper is used in another story, no significant difference in the dissipated energy in the structure is observed. The dissipated energy in the SP4 frame, where the first story has a yielding metallic damper and the second story has a friction damper, is slightly higher than in the SP5 frame. By examining the load-carrying capacity, maximum displacement generated, and energy dissipated in SP4 and SP5 frames, it seems that using yielding metallic dampers in lower stories and friction dampers in upper stories has a greater impact on improving the behaviour of the structure. However, since the studied structure is a two-story frame, reaching a definitive conclusion requires examining multiple structures of low, medium, and high-rise buildings.

8. Conclusion

In this project, the seismic performance of a two-story steel frame with yielding metallic dampers, friction dampers, and a combination of yielding metallic dampers and friction dampers has been investigated. The results of the analysis are as follows:

- The use of yielding metallic dampers and friction dampers reduces the base shear in the frame.
- The base shear in a frame with yielding metallic dampers used in both stories is lower compared to a frame with friction dampers used in both stories. Therefore, it can be concluded that the influence of yielding metallic dampers on reducing the base shear is greater than friction dampers.
- In frames where a yielding metallic damper is used in one story and a friction damper is used in another story, no significant difference in the base shear of the structure is observed. The base shear in the SP4 frame, where the first story has a yielding metallic damper and the second story has a friction damper, is slightly lower than the SP5 frame.
- The use of yielding metallic dampers and friction dampers reduces the maximum displacements generated in the frame.
- The maximum displacement in a frame with friction dampers used in both stories is lower compared to a frame with yielding metallic dampers used in both stories. Therefore, it can be concluded that the influence of friction dampers on reducing the maximum displacements in the structure is greater than yielding metallic dampers.
- In frames where a yielding metallic damper is used in one story and a friction damper is used in another story, no significant

difference in the maximum displacements generated in the structure is observed. The maximum displacements in the SP4 frame, where the first story has a yielding metallic damper and the second story has a friction damper, are slightly lower than the SP5 frame.

- The use of yielding metallic dampers and friction dampers increases the amount of energy dissipated in the frame.
- The energy dissipated in a frame with friction dampers used in both stories is higher compared to a frame with yielding metallic dampers used in both stories. Therefore, it can be concluded that the influence of friction dampers on increasing the energy dissipated in the structure is greater than yielding metallic dampers.
- In frames where a yielding metallic damper is used in one story and a friction damper is used in another story, no significant difference in the energy dissipated in the structure is observed. The energy dissipated in the SP4 frame, where the first story has a yielding metallic damper and the second story has a friction damper, is slightly higher than the SP5 frame.
- By examining the load-carrying capacity, maximum displacements generated, and energy dissipated in the SP4 and SP5 frames, it seems that using yielding metallic dampers in lower stories and friction dampers in upper stories has a greater impact on improving the behaviour of the structure. However, since the studied structure is a two-story frame, reaching a definitive conclusion requires examining multiple structures of low, medium, and high-rise buildings. Thus, the findings suggest that the combination of yielding metallic dampers and friction dampers can effectively improve the seismic performance of steel frames. Further research on structures of different heights is recommended to validate these conclusions

References

[1] Mahin, S. A. (1998). Lessons from damage to steel buildings during the Northridge earthquake. Engineering structures, 20(4-6), 261-270.

[2] Shokouri, A. (2019). The role of the metal damper in improving the seismic performance of steel frames with rigid and semi-rigid connections. Master's thesis, Islamic Azad University, Ramsar Branch, Iran.

[3] Hassanzadeh, J. (2015). Performance evaluation of a yieldable metal damper. Master's thesis, University of Birjand, Birjand, Iran.

[4] Wilson, C. M. D. (2005). Fuzzy control of magnetorheological dampers for vibration reduction of seismically excited structures. The Florida State University.

[5] DiSarno, L., & Elnashai, A. S. (2002). Seismic retrofitting of steel and composite building structures. Mid-America Earthquake Center CD Release 02-01.

[6] Moradi, A. (2017). Performance investigation of multi-damper controlled structures with varying numbers of stories. Master's thesis, Islamic Azad University, Torbat Heydariyeh Branch, Iran.

[7] Mirsafi, H., Azhdari Moghadam, M., Ghalenooy, M., Kashtgar, B. (2011). Analysis of 4 and 8-story steel structures equipped with friction dampers using ABAQUS software. Sixth National Civil Engineering Congress, Semnan University, Iran.

[8] Khaleghian, F., Tehrani Zadeh, M. (2008). Design of a new type of friction damper with a brake pad. Journal of Seismology and Earthquake Engineering, 9(4).

[9] Bayat, M., Zahraei, M. (2016). The role of friction damper in improving the seismic performance of steel frames with rigid and semi-rigid connections. Journal of Structure and Steel, 19, Summer 2016.

[10] Karami Mohammadi, R., Sarmast, H. (2005). Use of braced frames with friction dampers for lightweighting in structures, First International Conference on Earthquake and Lightweight Construction.

[11] Papadopoulos, P. K., Salonikios, T. N., Dimitrakis, S. A., & Papadopoulos, A. P. (2013). Experimental investigation of a new steel friction device with link element for seismic strengthening of structures. Struct. Eng. Mech, 46, 4.

[12] Amiri, J., Rahimi, H. (2012). "Investigation of optimal slip percentage for friction damper in rehabilitated steel buildings with energy-based design concept", Third National Conference on Structure and Steel and First National Conference on Light Steel Structures (LSF).

[13] Latour, M., Piluso, V., & Rizzano, G. (2014). Experimental analysis on friction materials for supplemental damping devices. Construction and Building Materials, 65, 159-176.

[14] Montuori, R., Nastri, E., & Piluso, V. (2014). Theory of plastic mechanism control for the seismic design of braced frames equipped with friction dampers. Mechanics Research Communications, 58, 112-123.

[15] Saeed Monir, H., & Fazalipoor, N. (2016). Application of a new cylindrical slit damper for mitigation of structural

vibrations. Journal of Civil and Environmental Engineering, 45(81), 29-43.
[16] Kamasi, M., Sharifi, M. (2015). "Investigation and comparison of seismic behaviour of dissipative braced frames equipped with XADAS and TADAS dampers in terms of energy absorption, ductility, and displacement", Innovative Researches in Civil Engineering, Architecture, and Urban Planning, Tehran, International Sound and Vision Conferences Center.
[17] Wada, A., Huang, Y.H., Yamada, T., Ono, Y., Sugiyama, S., Baba, M., Miyabara, T. (1997). Actual size and real-time speed tests for hysteretic steel damper. Proceedings of Stessa, Vol. 97, pp. 778-785
[18] Lee, M. H., Oh, S. H., Huh, C., Oh, Y. S., Yoon, M. H., Moon, T. S. (2002). Ultimate energy absorption capacity of steel plate slit dampers subjected to shear force. Steel Structures, Vol. 2, pp. 71-79.
[19] Chan, R., Albermani, F. (2008). Experimental study of steel slit damper for passive energy dissipation. Engineering Structures, Vol. 30, pp. 1058-1066, 2008.
[20] Oh, S.H., Kim, Y.J., Ryu, H.S. (2009). Seismic performance of steel structures with slit dampers", Engineering Structures, Vol. 31, pp. 1997-2008.
[21] Khoshnoudian, F., Kiani, M. (2010). "Performance evaluation of Slotted Steel Damper (SSD) in steel structures with moment frame system", First National Conference on Earthquake-Geotechnics, Mazandaran, Babolsar.
[22] Moshtagh, A., Tohidi Moghadam, V. and Saeed Monir, H. (2012). Study of progressive fracture on reinforced frames with duct slit damper. The 2nd National Conference on Earthquake-Geotechnic and Structures, Mazandaran.
[23] Saffari, H., Hedayat, A.A., "Poorsadeghi Nejad, M. (2013). Post-Northridge connections with slit dampers to enhance strength and ductility", Journal of Constructional Steel Research, Vol. 80, pp. 138-152.
[24] Fathi, S. (2016). Optimal distribution of rotational friction damper properties in building floors. Master's thesis, Mohaghegh Ardabili University, Ardabil, Iran.
[25] Vader, A. S. (2004). The influence of signature tower passive energy dissipating devices on the seismic response of long-span cable-supported bridges (Doctoral dissertation, Washington State University).
[26] Abaqus User’s Manual