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Seismic Performance Evaluation of Friction Dampers and Metallic Yielding Dampers in Steel Frame Structures

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ABSTRACT

In recent years, the use of control systems and energy dissipation devices has received widespread attention to reduce vibrations caused by dynamic loads and to improve the seismic performance of structures. Among these systems, metallic yielding dampers and friction dampers are notable, both of which are widely used in optimizing the seismic response of steel frames. In this study, the seismic behavior of two-story steel frames equipped with these two types of dampers—individually and in combination—has been investigated through numerical modeling in an analytical software environment under dynamic loading. For this purpose, five models were analyzed and compared: a reference frame without dampers, a frame with metallic yielding dampers, a frame with friction dampers, a frame with a metallic yielding damper on the first floor and a friction damper on the second floor, and vice versa. The results indicate that the use of dampers leads to an increase in energy dissipation capacity, a reduction in inter-story drifts, and a decrease in base shear. Furthermore, the findings reveal that the metallic yielding damper is more effective in reducing base shear, while the friction damper performs better in controlling displacements and enhancing energy absorption. Overall, the combined use of these two types of dampers can be an efficient approach to improving the seismic performance of steel frames.

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Introduction

Steel structures, as one of the most widely used building systems in the world, are always subjected to dynamic loads caused by earthquakes. Therefore, improving their seismic performance is a key issue in earthquake engineering. Recent earthquake experiences have shown that relying solely on the strength and ductility of the structure is not sufficient to ensure adequate safety against earthquakes, and there is a need for supplementary systems to reduce the input energy and inevitable vibrations. In this regard, various control systems have been developed, which are generally classified into two main groups: "seismic isolators" and "energy dissipation dampers" [1].

Earthquakes are one of the most significant natural hazards, always posing a serious threat to the safety and stability of structures, especially steel structures. Recent experiences with destructive earthquakes have shown that relying solely on the inherent strength and ductility of steel frames is not enough to reduce damage and severe vibrations. There is an increasing need to employ complementary methods for controlling the seismic response of structures. This highlights the importance of the current study, as improving the seismic performance of structures through the use of energy dissipation systems can play a significant role in enhancing safety, reducing reconstruction costs, and improving urban sustainability [4].

A review of previous studies shows that structural control systems are generally classified into seismic isolators and energy dissipation dampers. Among the various types of dampers, metallic yield dampers and friction dampers have attracted considerable attention from researchers and engineers due to their characteristics such as simple construction, reliable performance, and low cost. Various studies have shown that metallic dampers, through controlled plastic deformation, have a high capacity for absorbing earthquake energy, while friction dampers reduce displacements and the dynamic response of the structure through controlled sliding. However, direct comparisons of the performance of these two types of dampers under the same conditions, especially in their combined use, have been less studied [3].

Therefore, the goal of this research is to investigate and compare the seismic behavior of a two-story steel frame reinforced with metallic yield dampers and friction dampers, both separately and in combination. In this context, key structural responses such as base shear, relative displacement, and energy dissipation under seismic loading are analyzed and evaluated.

The justification for conducting this study is that the results can serve as a basis for the optimal selection and efficient design of control systems in steel frames. Additionally, the combined use of both types of dampers can offer a novel and effective solution to improve the seismic performance of structures, which is crucial for enhancing earthquake safety and reducing earthquake-related damages.

1. Background of Research

Numerous studies have been conducted on the application of different types of dampers in various structures. Mirseifi et al. [7] concluded that friction dampers apply a constant force opposite to the movement of the building, opposing its motion and significantly dissipating the input energy. Khaleghi and Tehrani-Zadeh [8] demonstrated in their studies that friction dampers have a special ability to reduce the vibrational energy of a structure under seismic forces. Bayat et al. [9] showed that the use of friction dampers increases the ductility of structures. Karami and Sarmast [10] and Papadopoulos et al. [11] found that friction devices significantly improve the resistance of bracing systems and skeletal structures against earthquakes, as well as their damage control potential. Amiri [12] showed in his studies that appropriate distribution of friction dampers controls lateral displacement and diaphragm rotation as much as possible. Latour et al. [13], Mantori et al. [14], and Monir et al. [15] concluded that adding a friction damper to a frame without dampers reduces its displacement by approximately 15%.

Kamasi et al. [16] concluded from their study on the effect of using slit steel dampers that structures equipped with slit steel dampers have greater ductility, and their displacements are reduced. Wada et al. [17] showed that slit steel dampers exhibit a stable hysteresis loop and after yielding, they tend to harden, which gradually increases the stiffness of the structure. Studies by Li et al. [18] and Chan et al. [19] have shown that the use of slit steel dampers significantly increases the ultimate energy absorption capacity of structures equipped with slit steel dampers. Oh et al. [20] demonstrated that increasing the length of the damper and the width of the strips increases the connection strength in skeletal structures. They also found that energy dissipation and plastic deformation occur only in dampers...

The concentrated slit dampers prevent the nonlinear behavior of beams and columns, avoiding their inelastic behavior. The research findings of Khoshnoodian and Kiani [21] show that adding a certain number of dampers in the floors is effective in improving the structural response. However, adding more dampers beyond a certain point does not significantly improve the structural response. Tohidi Moghadam and Saeed Monir [22] studied a new type of slit steel damper, where the cross-section is circular. Their results indicate that using these dampers in a diagonal bracing system, compared to the beam-to-column connection, has better performance and leads to a significant reduction in displacement and base shear. Safari et al. [23] introduced and examined new types of connections with slit dampers to increase the ductility of beam-column connections.

In this project, the seismic performance of friction dampers and metallic yield dampers in a steel frame is analyzed. The behavior of a two-story steel frame with a metallic yield damper, a friction damper, and the combination of both dampers is studied. The primary goal of the project is to assess the impact of using metallic yield dampers, friction dampers, and their combination in a two-story steel frame, particularly focusing on the maximum lateral displacement, base shear, and energy dissipation.

2. Research Methodology

This study was conducted using an analytical-numerical approach, where two-story steel frames were modeled under dynamic loading using finite element analysis in software. The seismic responses, including displacements, base shear, and energy dissipation, were analyzed and compared.

3. Dampers

3.1. Friction Dampers

Friction is used as a mechanism for energy dissipation. Mechanical engineers have long used this property to dissipate the kinetic energy of moving bodies. Friction brakes are an example of the use of friction 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. These dampers operate based on the frictional mechanism between rigid bodies sliding against each other. In essence, friction is an excellent energy dissipation mechanism and has been successfully applied to dissipate kinetic energy. Various materials have been used for the sliding surfaces, such as brake layers on steel, steel on steel, steel on brass, and combinations like graphite with bronze on stainless steel and other metal alloys.

The selection of base metals for friction dampers is crucial. Corrosion can reduce the assumed friction coefficient over the damper's service life. For example, carbon steel alloys tend to rust and corrode, affecting their surface properties over time. In contrast, brass and bronze, when in contact with low-carbon alloys, increase corrosion rates. Stainless steel, however, does not show significant additional corrosion when in contact with brass, making it more suitable for friction dampers. Friction dampers are highly effective, with their response being independent of frequency range and loading cycles, thus combining the potential for high performance with relatively low cost. These dampers fall into the category of hysteretic dampers, dissipating energy through displacement and sliding [5].

All existing friction dampers essentially work in the same manner: one part remains fixed, while the other part slides dynamically on it. Sliding occurs once a specified force threshold is reached, following Coulomb's law of friction. Once this threshold is surpassed, sliding and motion begin. The configuration of the sliding surfaces results in various types of friction dampers, including more complex combinations like the Pall friction damper [24].

3.2. Metallic Yield Dampers

By understanding the crystalline structure of different metals, the damping behavior of metals under cyclic loading can be studied, and desirable damping properties can be observed before the yield stress point is reached. One approach to utilizing this property involves shaping a piece of metal into a form (usually an isosceles triangle) that shows damping behavior under dynamic loading and placing it in the joints of the structural members. The material, shape, and placement of these dampers should be selected such that their damping properties are not adversely affected by various environmental factors over the structure's lifespan.

Metals used for metallic yield dampers typically need to have appropriate hysteresis behavior, high fatigue resistance, relatively high strength, and low sensitivity to temperature variations. These dampers primarily rely on elastic deformations of the metal and internal friction from the crystal structures, resulting in energy dissipation.

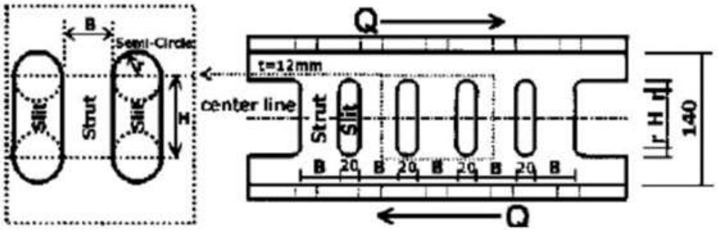
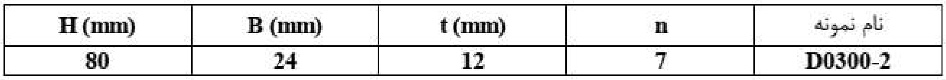


Figure 1: Sample of the metallic slit damper being studied, as presented by **Li et al.** (2002) [18].



H (mm)	B (mm)	t (mm)	n	نام نمونه
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Table 1: Geometric specifications of the metallic slit damper being studied, according to **Li et al.** (2002) [18].

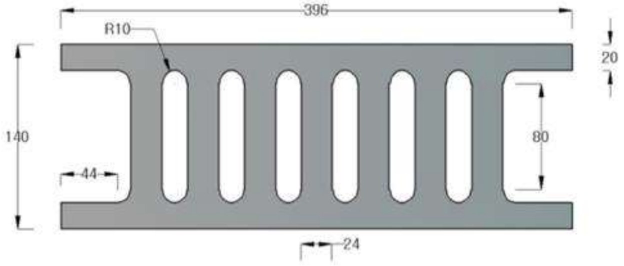
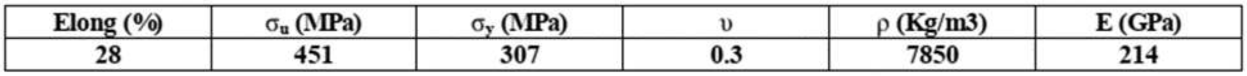


Figure 2: Geometrical dimensions of the sample of the shape-controlled metallic damper under investigation [18].

Table 2: Specifications of the steel used in the sample of the metallic damper under investigation (Li et al., 2022).



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

The element shapes used are in HEX format, as shown in Figure 3. For the Solid element used, an 8-node C3D8 mesh type has been considered. It is worth mentioning that the mesh size is 10x10 mm, which results in the creation of 1380 elements.

The surface of the specimen is constrained in all directions:

U1 = 0, U2 = 0, U3 = 0, UR1 = 0, UR2 = 0, UR3 = 0.

The specimen is only subjected to horizontal displacement in the X direction at the reference point by 66 mm in a linear manner, with the weight effect of the specimen neglected. In Figure 4, the color contour of the von Mises stress of the specimen after loading and analysis is shown. The force-displacement curve of the numerical model created in Abaqus software and the experimental specimen are compared in Figure 5. The results indicate a satisfactory agreement between the numerical and experimental models.

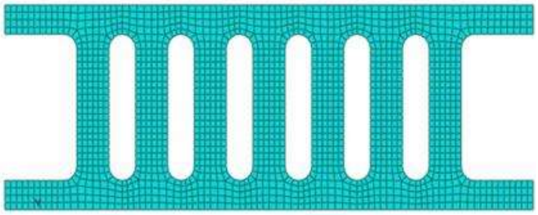


Figure 3: Partitioning and Meshing of the Analyzed Model

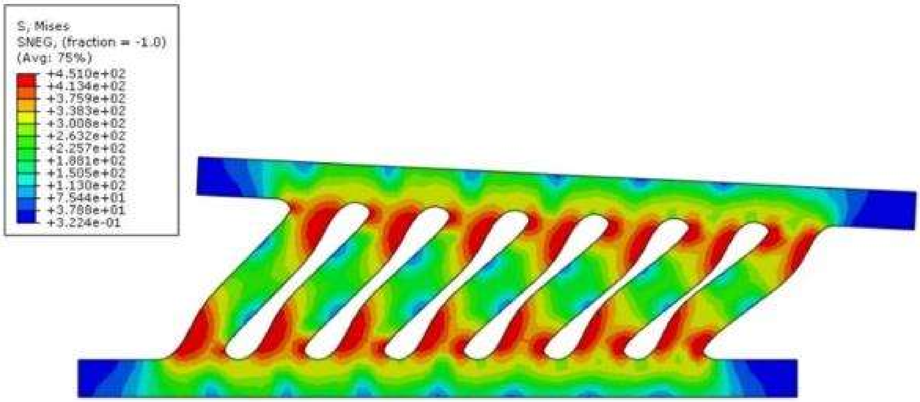


Figura 4: Contour color distribution of von Mises stress in the examined sample.

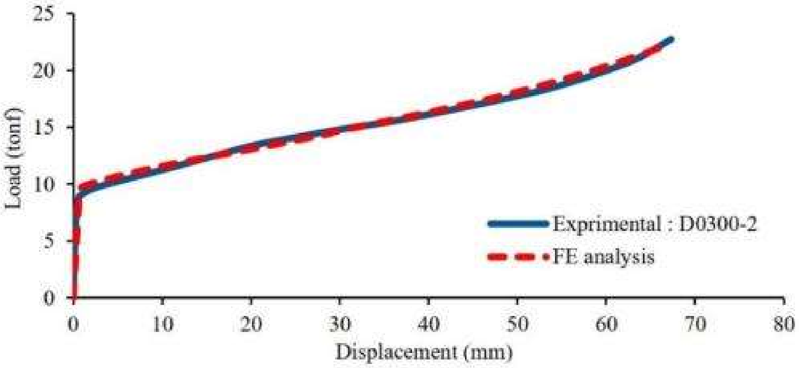


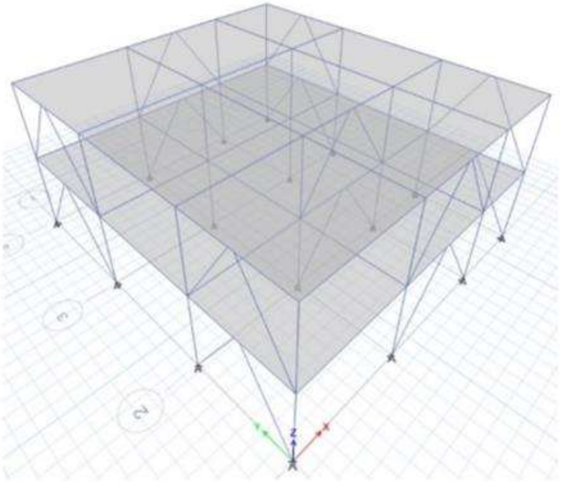
Figure 5: Comparison of Force-Displacement Curve of the Experimental and Analytical Specimen

5- Modeling of the Analyzed Buildings in ETABS Software

A two-story building with an out-of-plane bracing system has been designed. In this design, the seismic considerations of the Building Design Code for Earthquake Resistance (Standard 2800) were taken into account. The design of the building was carried out using ETABS software. Then, based on the steel sections for the beams, columns, and braces, the structural frames were simulated in ABAQUS to examine the forces generated in the frame members and the displacement of the nodes. After applying the loads and the model of their application to the structure, the system response and the required parameters were determined based on the analysis.

The mentioned steel buildings have identical floor plans, with each floor area measuring 200 m². The height of each floor is considered to be 2.3 meters. The lateral load-resisting system of the building is a two-way bracing system. The connection of the beams to the columns is simple. All structural components are made of St37 structural steel, with an ultimate stress of 3700 kg/cm² and a yield stress of 2400 kg/cm². The 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 were calculated assuming the structure is located in seismic zone 4 of Iran. The roof of the buildings is made of block beams with one-way slab direction. The structural plan and the 3D image of the two-story frame modeled in ETABS are presented in Figures 6 and 7, and the design results are shown in Table 4.

After designing the structure in ETABS, a single span with a diverging brace was selected, and simulations were carried out in Abaqus for the required analysis. In this study, five different models were used with various configurations, the specifications of which are listed in Table 5.



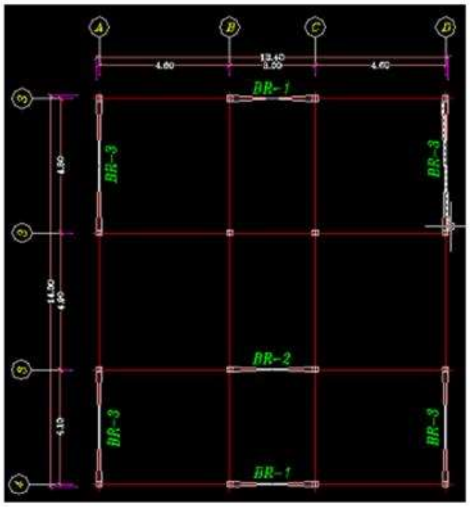


Figura 6: Plan of the structure under investigation. **Figura 7:** 3D image of the two-story steel structure with divergent braces.

Tabula 3: Design results of the members of the two-story steel building.

Floors	Columns	Main beams	Bracing
Ground floor	**IPB140**	**IPE240**	**IPE140**
First floor	**IPB140**	**IPE240**	**IPE140**

Tabula 4: Dispositio amortizatorum in exemplis constructis.

Model name	Number of floors	Type damper of brace	Type damper of the second floor	Type of damper on the second floor	Location of brace placement	Length of damper span placement
SP1	2	Divergent	Without damper	Without damper	External frames	Without damper
SP2	2	Divergent	Metallic yielding,	Metallic yielding,	External frames	4/8 meters
SP3	2	Divergent	frictional	frictional	External frames	4/8 meters
SP4	2	Divergent	Metallic yielding,	frictional	External frames	4/8 meters
SP5	2	Divergent	frictional	Metallic yielding,	External frames	4/8 meters

6. Phases of Modeling

To create the geometric shape of components that will later be used for analysis, the Part module is used. In Figure 8, the modeled frame in ABAQUS software is shown. The type of analysis intended in this modeling is **Dynamic-Explicit** analysis. Also, in the given modeling, **Nlgeom** is activated, meaning Abaqus computes nonlinear geometry. Considering nonlinear geometry is crucial in cases where loading on the model leads to large displacements [26].

In the software, welding can be defined in both flexible and rigid forms, and the interaction between surfaces can be applied accordingly. In this study, both connected components were welded together using the **Tie** constraint. Since the load must be applied to the center of the surface to avoid additional torque during loading, by defining a reference point at the floor level and constraining this point with the multiple **MPC** constraint, the conditions can be applied. The load applied to the structure is the **Tabas earthquake**. The Tabas earthquake occurs in three directions: X, Y, and Z. The earthquake lasts for 33 seconds; however, since each earthquake consists of three phases: the initial shaking, the effective time, and the earthquake's decay time, and the greatest effect and damage occurs in the time frame between 4 to 20 seconds, it is noted that after the 20th second, the acceleration is negligible. Therefore, this time frame is used in the analysis, which reduces computation time and ensures convergence of results. In Figure 9, the x-component mapping of the Tabas earthquake is shown.

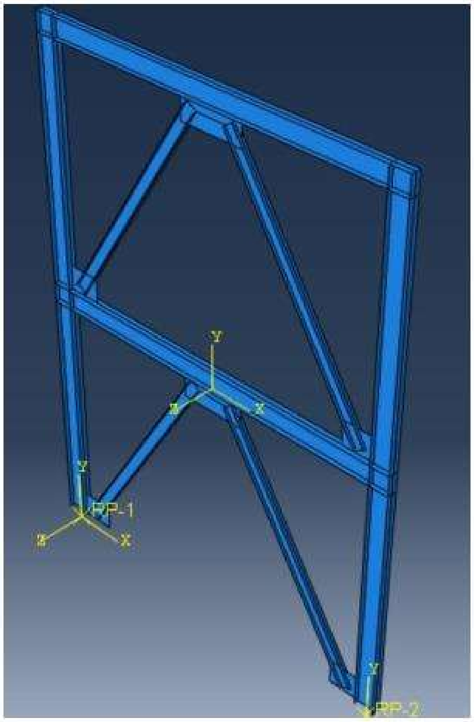


Figure 8: Image of a one-span, two-story frame with an outrigger braced frame modeled in ABAQUS software.

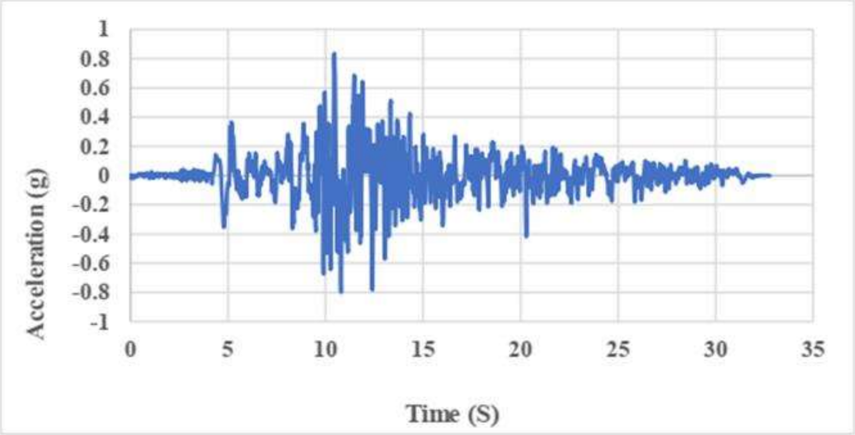


Figure 9: Tabas acceleration record in the X direction.

Considering the type of analysis and the aforementioned explanations, for meshing, three-dimensional stress family elements and a reduced integration node-connected type, denoted by C3D8R, have been used (Figure 10).

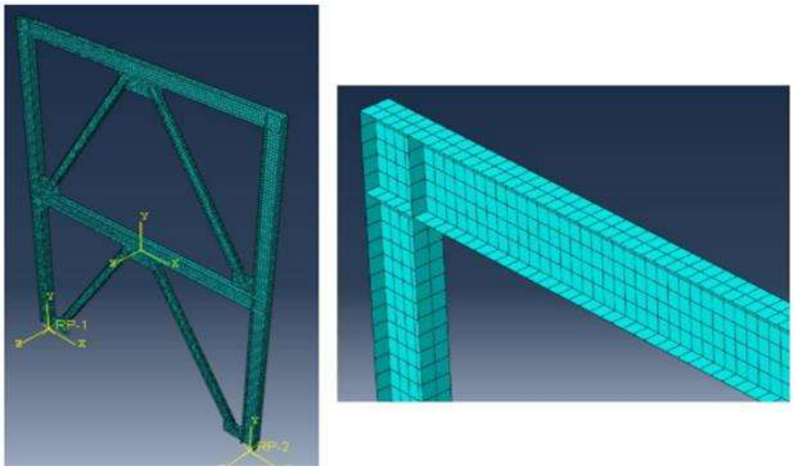


Figure 10: Meshed frame braced with an outrigger brace.

7. Examination of the frames under consideration

As mentioned, in this study, five frames (with and without dampers) are examined. By analyzing the hysteresis curves of each frame, the load-bearing capacity, maximum displacements generated, and the energy dissipation and absorption capability of the frames are evaluated. In Figures 11 and 12, the colored stress contours of Von Mises and Tresca in frame SP1 are shown.

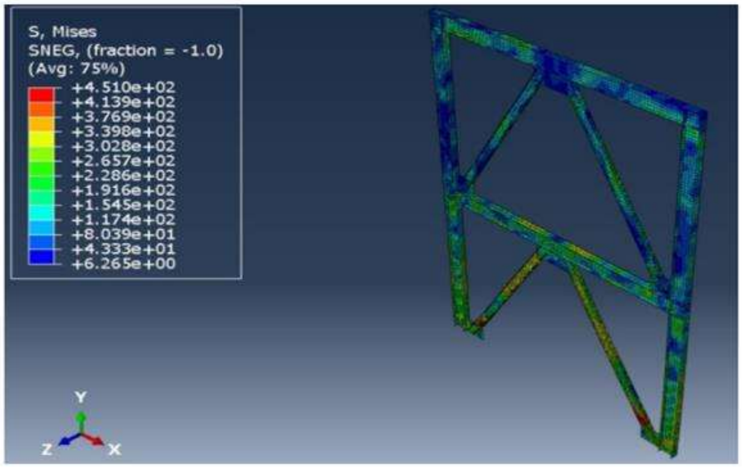


Figure 11: Colored contour of **Von Mises** stress distribution in the frame modeled in ABAQUS software

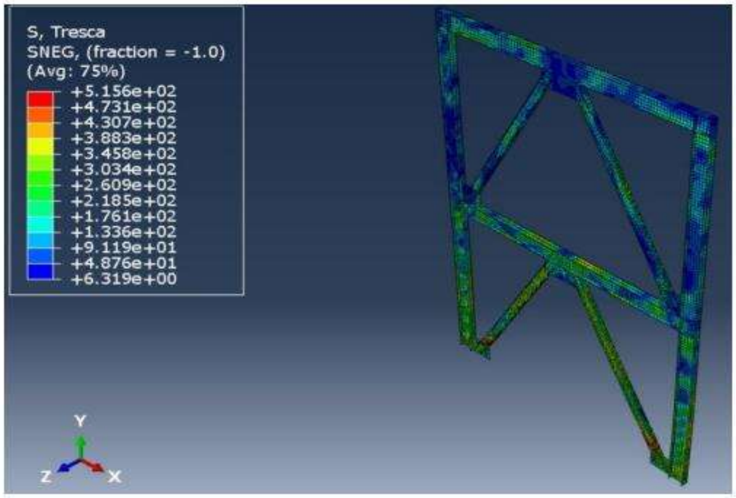


Figure 12: Colored contour of Tresca stress distribution in the frame modeled in ABAQUS software.

1-7. Base shear examination of the frames under consideration

The base shear in the frames braced with outrigger braces, both without dampers and with the use of friction and metallic yielding dampers, is examined with the details provided in Table 5. The results obtained are shown in Figure 13 and Table 5.

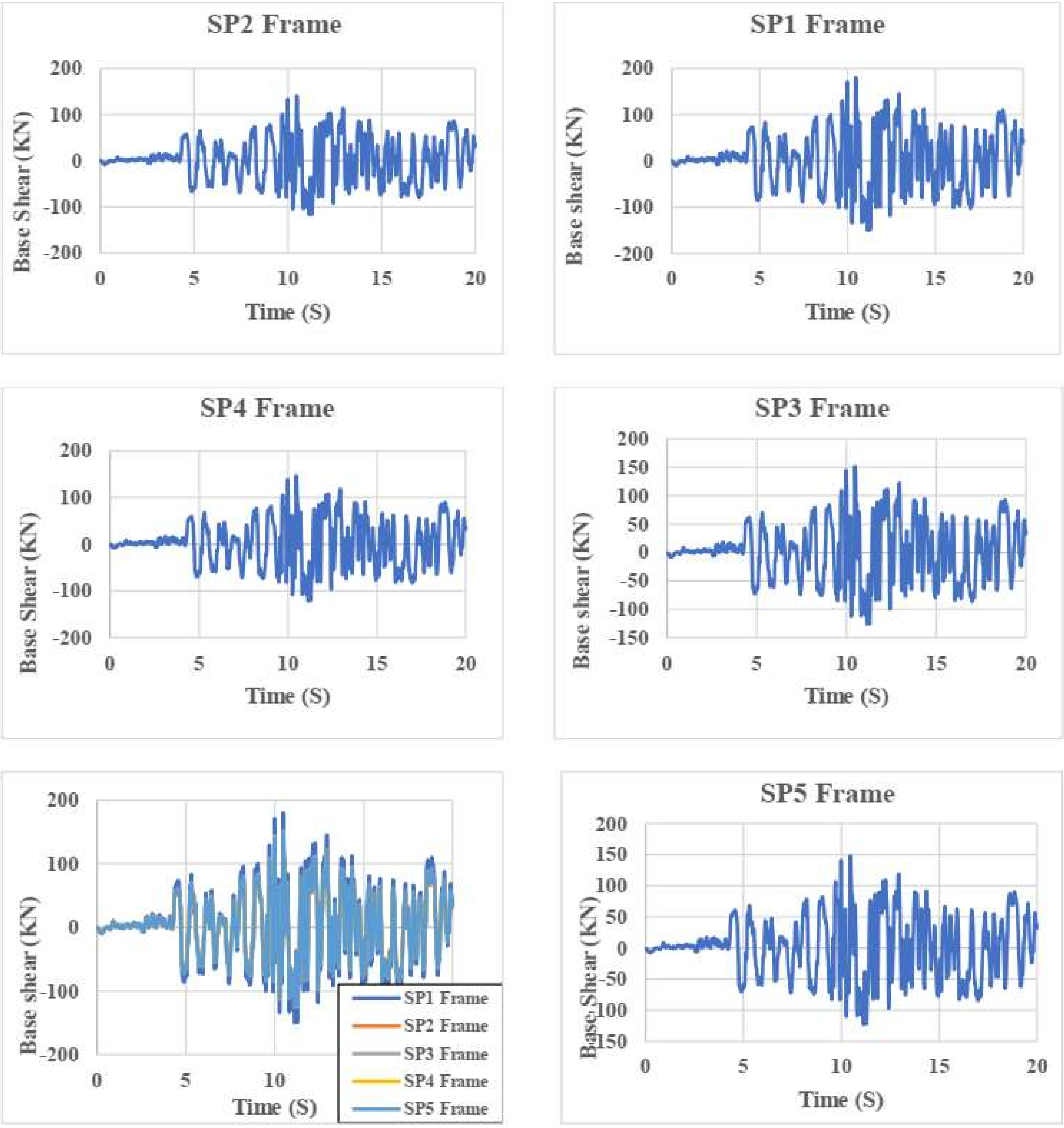


Figure 13: Base shear generated in frames SP1 to SP5.

The analysis of the results obtained shows that the use of metallic yielding dampers, as well as friction dampers, reduces the base shear of the examined frame. The base shear in a frame where metallic yielding braces are used in both stories is lower compared to a frame where friction braces are used in both stories. Therefore, it can be concluded that the effect of metallic yielding braces in reducing the base shear is greater than that of friction braces. In frames SP4 and SP5, where one story has metallic yielding braces and the other story has friction braces, no significant difference in the base shear of the structure is observed. The base shear in frame SP4, which has a metallic yielding damper in the first story and a friction damper in the second story, is slightly lower than that of frame SP5.

Table 5: Base shear applied to the braced frames under examination.

Base shear (kN)	Name of the frame under consideration
180.41	SP1
140.72	SP2
151.54	SP3
146.13	SP4
147.93	SP5

2-7. Examination of the maximum displacements generated in the frames under consideration

The maximum displacements generated in the outrigger-braced frames, both without dampers and with the use of friction and metallic yielding dampers, are examined with the details provided in Table 5. The results obtained are presented in Figure 14 and Table 6.

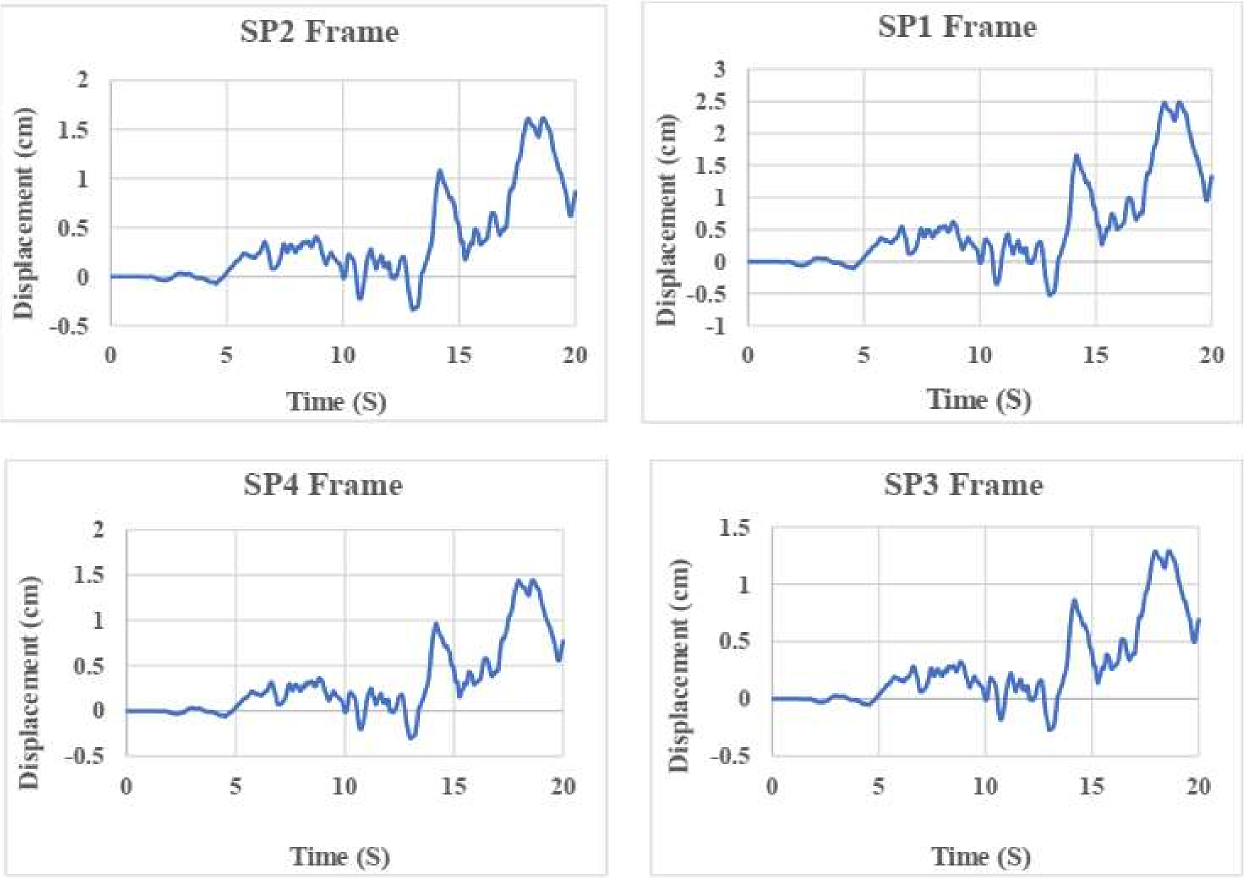


Figure 14: Base shear generated in the frames.

Table 6: Maximum displacements generated in the examined braced frames.

Maximum displacement generated (cm)	**Name of the frame under consideration**
2.48	SP1
1.61	SP2
1.29	SP3
1.44	SP4
1.49	SP5

The analysis of the results obtained shows that the use of metallic yielding dampers, as well as friction dampers, reduces the maximum displacements generated in the examined frame. The maximum displacement generated in a frame where friction braces are used in both stories is lower compared to a frame where metallic yielding braces are used in both stories. Therefore, it can be concluded that the effect of friction braces in reducing the maximum displacements generated in the structure is greater than that of metallic yielding braces. In frames SP4 and SP5, where one story has metallic yielding braces and the other story has friction braces, no significant difference in the maximum displacements generated in the structure is observed. The maximum displacements generated in frame SP4, which has a metallic yielding damper in the first story and a friction damper in the second story, is slightly lower than that of frame SP5.

3-7. Examination of energy absorption and dissipation capability in the frames under consideration

The energy absorption and dissipation capability in the outrigger-braced frames, both without dampers and with the use of friction and metallic yielding dampers, are examined with the details provided in Table 5. The results obtained are shown in Figure 16 and Table 7. The analysis of the results reveals that the use of metallic yielding dampers, as well as friction dampers, increases the energy dissipated in the examined frame. The energy dissipated in a frame where friction braces are used in both stories is greater than in a frame where metallic yielding braces are used in both stories. Therefore, it can be concluded that the effect of friction braces in increasing the energy dissipated in the structure is greater than that of metallic yielding braces.
In frames SP4 and SP5, where one story has metallic yielding braces and the other story has friction braces, no significant difference in the energy dissipated in the structure is observed. The energy dissipated in frame SP4, which has a metallic yielding damper in the first story and a friction damper in the second story, is slightly greater than that of frame SP5.
By examining the load-bearing capacity, maximum displacements generated, and energy dissipated in frames SP4 and SP5, it appears that using metallic yielding dampers in the lower

stories and friction dampers in the upper stories has a more significant effect on improving the behavior of the structure. However, since the examined structure is a two-story frame, a definitive conclusion requires the examination of various low-rise, mid-rise, and high-rise structures.

Table 7: Maximum Displacements Generated in the Analyzed Braced Frames

Maximum displacement generated (cm)	Name of the frame under consideration
2.48	SP1
1.61	SP2
1.29	SP3
122497.6	SP4
120627.4	SP5

Conclusion

In this project, the performance of friction dampers and metallic yielding dampers in a steel frame structure were analyzed. Specifically, the behavior of a two-story steel frame equipped with a metallic yielding damper, a friction damper, and a combination of both was examined. The results indicate the following:

1. The use of metallic yielding dampers, as well as friction dampers, reduces the base shear of the frame.
2. The base shear in a frame where both stories are equipped with metallic yielding braces is lower compared to a frame where both stories use friction braces. Therefore, it can be concluded that the effect of metallic yielding braces in reducing base shear is more significant than that of friction braces.
3. In frames where one story is equipped with metallic yielding braces and the other with friction braces, no significant difference is observed in the base shear. The base shear in frame SP4, where the first story has a metallic yielding damper and the second story has a friction damper, is slightly lower than in frame SP5.
4. Both metallic yielding dampers and friction dampers reduce the maximum displacement of the frame.
5. The maximum displacement in a frame where both stories are equipped with friction braces is lower than in a frame where both stories have metallic yielding braces. Therefore, it can be concluded that the effect of friction braces in reducing maximum displacements is greater than that of metallic yielding braces.
6. In frames where one story is equipped with a metallic yielding damper and the other with a friction damper, no significant difference is observed in the maximum displacements. The maximum displacement in frame SP4, which has a metallic yielding damper in the first story and a friction damper in the second story, is slightly lower than in frame SP5.
7. The use of both metallic yielding dampers and friction dampers increases the amount of energy dissipated in the frame.

8. The energy dissipated in a frame where both stories use friction braces is higher compared to a frame where both stories are equipped with metallic yielding braces. Therefore, it can be concluded that the effect of friction braces in increasing energy dissipation is more significant than that of metallic yielding braces.
9. In frames where one story has a metallic yielding damper and the other has a friction damper, no significant difference in energy dissipation is observed. The energy dissipated in frame SP4, which has a metallic yielding damper in the first story and a friction damper in the second story, is slightly higher than in frame SP5.
10. Based on the analysis of load-bearing capacity, maximum displacement, and energy dissipation in frames SP4 and SP5, it appears that using metallic yielding dampers in the lower stories and friction dampers in the upper stories has a more significant impact on improving the structural behavior. However, since the structure being analyzed is a two-story frame, a conclusive result requires further investigation on multiple short, mid-rise, and tall buildings.

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