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Research Paper

Seismic Performance Analysis of a 15-Story Steel Structure Equipped with Viscous Fluid Dampers and Diverse Frame Systems

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Abstract

Ensuring seismic resilience and optimizing structural response under earthquake excitations are critical aspects of modern performance-based seismic design. This study conducts a comprehensive numerical investigation into the seismic behavior of a 15-story steel structure equipped with viscous fluid dampers (VFDs) and compares its performance with three alternative lateral force-resisting systems: special divergent braced frames (SDBFs), special converging braced frames (SCBFs), and medium bending frames (MBFs). The analyses employ nonlinear time-history simulations and pushover analysis using ETABS to evaluate seismic response parameters, including base shear, inter-story drift ratios, residual displacements, and fundamental structural period. The results reveal that VFD-equipped structures exhibit superior seismic performance, achieving a reduction of up to 72% in base shear and 73% in peak lateral displacement compared to conventional bracing and frame systems. Furthermore, the integration of VFDs leads to a remarkable 106% reduction in the fundamental period, significantly enhancing energy dissipation capacity and mitigating structural damage. These findings underscore the efficacy of viscous dampers as a passive control mechanism, providing enhanced structural stability, reduced seismic vulnerability, and improved post-earthquake functionality, making them a viable solution for high-rise steel structures in seismically active regions.

Keywords: Seismic control, Viscous damper, Energy dissipation, Time history

1. Introduction

In the field of seismic engineering, enhancing the seismic resilience of buildings, particularly high-rise structures, remains a critical concern [1]. Earthquake-induced forces can cause severe structural damage, leading to significant financial losses and potential loss of life. The primary objective of seismic design is to mitigate the impact of these forces while ensuring the safety of both the structure and its occupants. One of the most effective methods for improving seismic performance is the implementation of energy dissipation systems, with viscous fluid dampers (VFDs) being among the most extensively researched and widely applied solutions [2-4]. These dampers are specifically designed to absorb and dissipate the kinetic energy generated by seismic activity, thereby reducing the forces transmitted to the structure. This mechanism enables improved control over the structural response during seismic events [5-7]. A viscous fluid damper is a passive damping system comprising a piston that moves within a fluid-filled chamber. When the structure experiences motion due to seismic forces, the damper counteracts this movement by generating resistance within the fluid, converting mechanical energy into heat and effectively dissipating it. This process significantly reduces the amplitude of structural vibrations, thereby minimizing displacement, base shear, and overall damage [8]. The advantages of VFDs are particularly pronounced in high-rise buildings, where the effects of seismic motions are often amplified due to the structure's height. VFDs contribute to reducing lateral displacements, enhancing structural response time, and improving energy absorption, ultimately preventing excessive inelastic deformations [9-11]. In conjunction with VFDs, various structural systems are employed to enhance overall building performance during seismic events. These systems include 7-divergent braces, special converging braces, and medium bending frames, each playing a crucial role in optimizing lateral stiffness, energy dissipation capacity, and overall structural integrity under dynamic seismic forces. When integrated with VFDs, these systems produce a synergistic effect, leading to superior seismic performance. In structures incorporating viscous fluid dampers, VFDs are strategically placed at critical locations, typically at floor levels or at junctions of structural elements such as beams and columns. These dampers function as buffers, mitigating peak acceleration and displacement caused by seismic movements. A 3D representation of such structures would typically illustrate the placement of dampers within the building's framework, often between columns or along the façade, where they provide maximum benefit [12-14]. The size and capacity of the dampers can be customized based on the seismic risk level and the specific design requirements of the building. Within this system, VFDs effectively reduce base shear and enhance occupant safety by limiting excessive movement and vibrations. The 7-divergent brace is a specialized bracing system designed to enhance the stability and lateral resistance of a building's frame against seismic forces. It consists of multiple braces radiating from a central node, thereby optimizing force distribution [15]. The configuration of these braces improves both stiffness and energy dissipation capacity during seismic events. A 3D visualization of this system would depict braces extending in multiple directions, forming a rigid and highly stable framework. These braces, typically arranged diagonally within the building's frame, efficiently transfer lateral forces to the foundation [16,17]. When combined with VFDs, this system facilitates a more uniform distribution of seismic forces, significantly reducing the risk of localized structural failure. The special converging brace system consists of braces converging towards a central point, typically located at the building's core, thereby enhancing lateral stiffness. This configuration efficiently resists lateral seismic forces by distributing them across the structural elements in a converging pattern [18]. These braces, which are typically positioned diagonally within the frame, are also space-efficient as they integrate seamlessly into the building's core or external frame [19]. A 3D visualization of this system would show braces converging toward specific central points on each floor, offering robust support while maintaining design flexibility. When combined with VFDs, these braces serve as strong force-resisting components, reducing structural displacement and base shear while facilitating effective seismic energy dissipation. A medium bending frame is a structural system designed to provide balanced resistance against both vertical and lateral forces. It is engineered to withstand moderate bending moments and shear forces, making it particularly suitable for structures subjected to medium-intensity seismic forces. The frame consists of beams and columns designed to resist bending and shear while maintaining flexibility [20]. A 3D representation of this system would typically depict a configuration of rigid beams and columns that evenly distribute forces across the structure. When integrated with VFDs, the frame effectively reduces lateral displacements and prevents excessive building motion during seismic events, thereby minimizing structural damage and enhancing overall seismic performance. Several studies have investigated the effectiveness of viscous fluid dampers and other seismic resistance systems

Shaya Far et al. (2016) [12] analyzed the seismic performance of regular and irregular steel frames equipped with viscous fluid dampers. In contrast, the present study provides a more precise assessment of four different structural systems, demonstrating a more substantial reduction in base shear, displacement, and structural period.

Shariati et al. (2020) [8] focused on optimizing the placement of viscous fluid dampers in high-rise buildings. The present study extends this research by examining the combined effects of these dampers with different frame systems in 15-story structures.

Khodabandeh et al. (2019) [3] evaluated the impact of viscous fluid dampers in adjacent buildings. However, the present study not only investigates the effectiveness of these dampers but also explores their integration with other resistance systems, employing more precise simulations for dynamic modeling.

Alehojjat et al. (2021) [10] examined the equivalent damping effects of viscous fluid dampers in steel structures. The present study expands upon this by providing a more comprehensive analysis of various resistance systems, including viscous dampers and converging braces, while incorporating more accurate modeling techniques.

Khosravi et al. (2021) [1] assessed the combined effects of viscous fluid dampers and converging braces. The present study employs more advanced dynamic simulations and nonlinear modeling while evaluating multiple structural systems.

Sadeghi et al. (2022) [5] focused on the performance of a single system, flexural frames. In contrast, the present study provides a comparative analysis of four different seismic resistance systems, offering a more holistic evaluation.

This research not only investigates the effectiveness of viscous fluid dampers but also evaluates the seismic performance of various frame systems, including flexural, divergent, and convergent braces. The use of dynamic simulations and nonlinear modeling in ETABS software ensures high analytical accuracy. The findings demonstrate that viscous fluid dampers outperform other systems in reducing base shear, displacement, and structural period. The primary objective of this study is to assess and compare the seismic performance of four distinct resistance systems in 15-story steel structures: viscous fluid dampers, divergent braces, convergent (diagonal) braces, and flexural frames. These systems are analyzed using time-history dynamic analysis and nonlinear modeling via ETABS software. The results indicate that viscous fluid dampers significantly mitigate seismic forces compared to other systems, effectively reducing base shear, displacement, and structural oscillation periods while minimizing damage to structural components. This study highlights the role of these resistance systems in optimizing structural design, emphasizing principles such as strength, flexibility, and durability to enhance the safety and performance of buildings against seismic forces. The main innovation of this research lies in the identification of viscous fluid dampers as an efficient and highly effective seismic resistance system for high-rise structures. In addition to improving energy absorption capacity, this system substantially reduces structural damage and enhances overall stability under dynamic loads. Compared to other resistance systems, such as flexural frames and wind braces, viscous fluid dampers exhibit superior performance in mitigating structural damage and increasing resilience, particularly in the upper floors of high-rise buildings.

2. Characteristics of Structural Control Systems

Structural vibration control systems play a crucial role in enhancing the seismic performance of buildings. According to the American Society of Civil Engineers (ASCE), these systems are designed to reduce a structure's displacement and acceleration response. They are generally classified into three main categories: passive, active, and semi-active systems. Passive systems, such as seismic isolators and viscous and viscoelastic dampers, dissipate vibration energy without requiring external power, thereby improving a structure's performance during seismic events. In contrast, active control systems regulate the dynamic response of a structure in real time by applying control forces through sensors and processors. However, these systems require external power sources and complex control mechanisms. Semi-active systems, which combine passive and active approaches, adjust mechanical properties such as stiffness and damping with minimal energy consumption. This adaptability enhances a structure's response to seismic loading. Semi-active methods, which utilize intelligent algorithms and decentralized control, are more efficient than fully active methods, as they reduce floor drift, foundation shear, and post-earthquake repair costs. In recent years, hybrid systems that integrate multiple control strategies have gained attention. By combining the advantages of active and passive systems, these hybrid approaches optimize seismic performance and increase structural stability under critical conditions. Research indicates that modern technologies in vibration control, such as advanced damping systems, play a significant role in developing more effective solutions for structural reinforcement. Figure 1 illustrates various structural control systems, including active, semi-active, passive, and hybrid control methods.

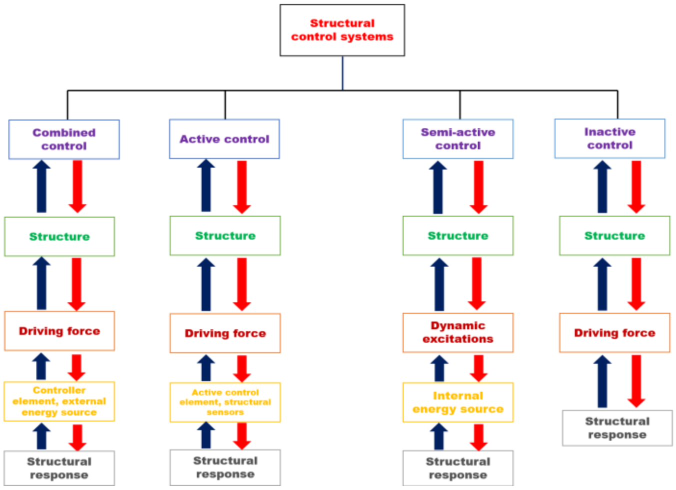


Fig. 1. Classification of structural control systems, including passive, active, semi-active, and hybrid methods for enhancing seismic performance

2.1. Fluid Viscous Dampers

Viscous damper systems, also known as viscous dampers, are hydraulic devices designed to dissipate kinetic energy generated by seismic vibrations or mitigate impacts between structures. These devices are highly versatile and can be engineered to absorb specific loads, such as seismic and wind-induced forces, while simultaneously allowing the structure to accommodate movements resulting from thermal expansion and contraction [7]. A typical viscous fluid damper consists of a cylinder, a highly viscous fluid or oil, a piston, a piston rod, an inner protective cover, and other essential components [8]. The damper is strategically installed within the bracing frame of the structure, where it absorbs a portion of the seismic energy transmitted to the building. By reducing the energy demand on structural elements, it effectively minimizes the risk of structural failure [9] (as illustrated in Figure 2).

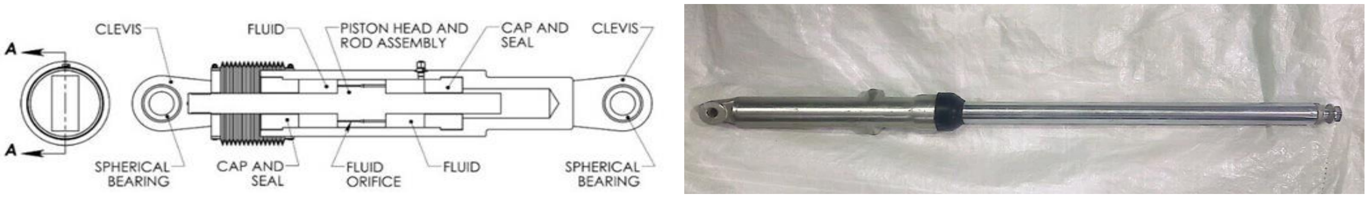


Fig 2. Schematic representation of the viscous damper and its components

3.Validation

To ensure the accuracy of the numerical analyses and modeling conducted in ETABS, it is essential to compare the results of the present study with those from a relevant and reliable research article. This validation process serves to assess the correctness of the analysis and verify the compatibility of the results with those from previous studies. For the validation of the analyses performed in this study, the research conducted by Mahbubeh Mirzaei et al. [11] was selected. In their study, 4-story steel frames, both with and without viscous dampers, were modeled in ETABS and evaluated using seismic retrofit guidelines and nonlinear static methods. The results indicated that the inclusion of viscous dampers significantly reduced seismic force effects and performance failure levels. Moreover, the use of dampers in taller structures had a more pronounced effect on reducing earthquake forces when compared to shorter structures.

3.1. Validation Methodology

The validation process includes the following steps:

Selection of Reference Model: The selected reference article provides a numerical model with geometric characteristics and material properties similar to those of the current study, utilizing comparable analytical methods to examine the behavior of structures under seismic loads. Modeling in ETABS: Four-story steel frames, both with and without viscous dampers, were modeled in ETABS following the methodology of the reference study. The nonlinear behavior of structural members, damper hysteresis properties, and the interaction between the structure and dampers were incorporated into the analysis. Numerical Analysis and Loading: The models were subjected to nonlinear static (pushover) analysis and nonlinear time-history analysis. Recorded earthquake accelerograms from both near-field and far-field earthquakes were utilized in accordance with the reference study. Comparison Criteria and Validation:

- Base shear
- Inter story drift ratio
- Performance levels according to seismic retrofit guidelines
- Energy distribution and absorption by dampers

3.2. Analysis and Results

The numerical analysis results from this study demonstrate that the inclusion of viscous dampers leads to a significant reduction in base shear and inter-story drift, thereby enhancing seismic performance. These findings align with the results of the reference study, confirming the accuracy of the modeling and analysis conducted. The comparison of results under three different loading patterns, uniform loading, first-mode shape loading, and dynamic time-history loading, reveals that viscous dampers substantially reduce earthquake-induced lateral forces and effectively control nonlinear displacements in the structure. Compared to braced frames and steel moment-resisting frames, the system equipped with viscous dampers exhibits superior performance in reducing displacement demand and absorbing energy, as illustrated in Figure 3 and Table 1. Given the consistency of the results in this study with those of the reference paper, it can be concluded that the numerical modeling and analyses conducted in this research are accurate and reliable. This validation confirms the correctness of the modeling process, the numerical analysis settings, and the assumptions made in this study, thereby providing confidence in extending the results to similar structures. Furthermore, this validation step reinforces the reliability of the numerical methods employed, ensuring that the findings are applicable to other comparable steel structures equipped with viscous dampers.

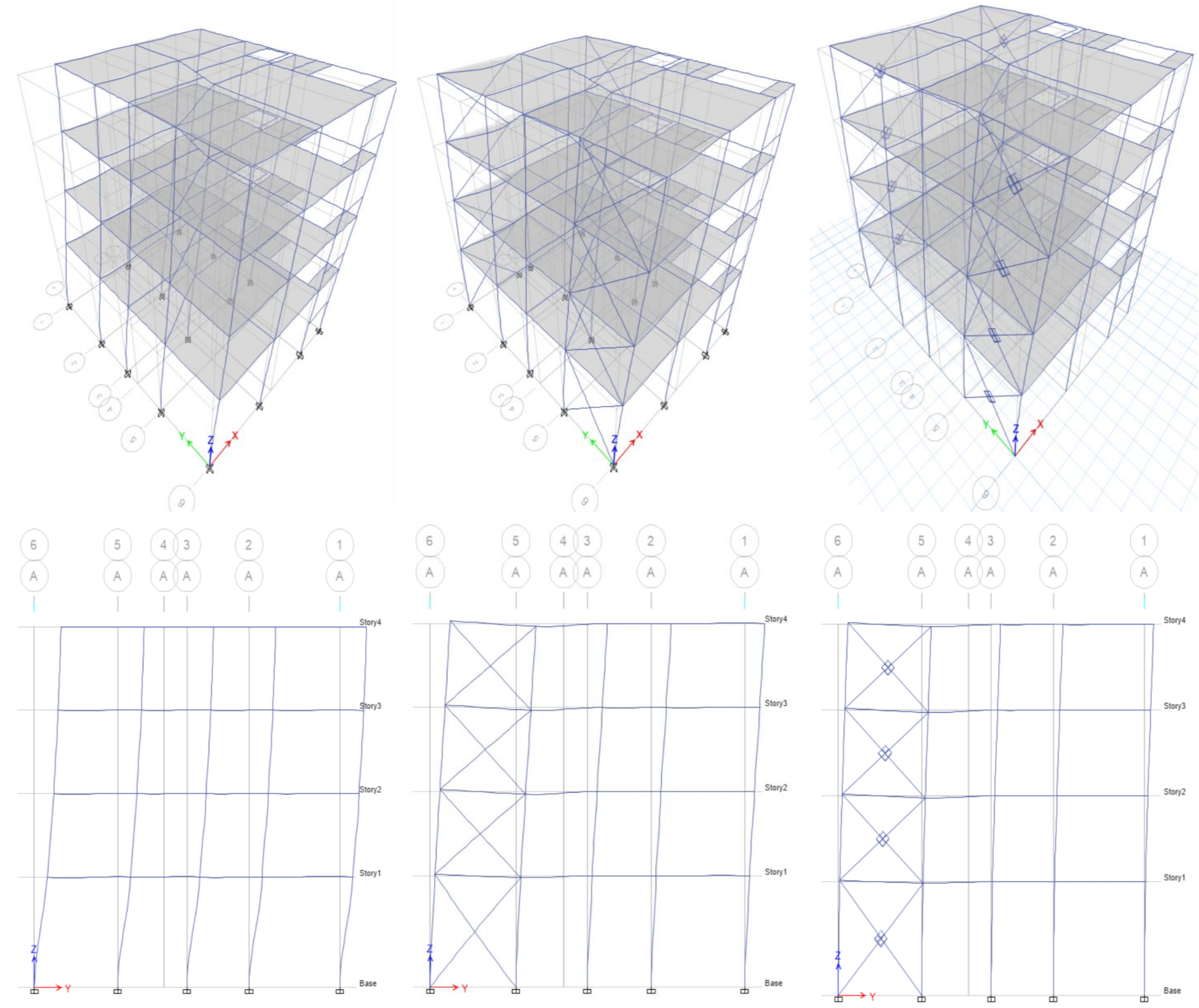


Fig. 3. Comparison of the obtained results and the reference article model from ETABS software

Table 1 provides a detailed comparison between the modeling parameters and analysis results of this study and the reference paper.

Table 1. Comparison of the numerical model of the present study with the reference study

Characteristic	Current Study Model	Reference Study Model (Mirzaei et al.)	Degree of Conformance
Structure Type	4-story steel frame	4-story steel frame	Complete
Lateral Load-Resisting System	Steel moment frame equipped with viscous damper	Steel moment frame equipped with viscous damper	Complete
Seismic Analysis Method	Nonlinear static analysis (Pushover) and nonlinear time history analysis (NLTHA)	Nonlinear static analysis (Pushover) and time history analysis (NLTHA)	Complete
Nonlinear Behavior Modeling	Use of FEMA-356 plastic hinges and viscous damper behavior model	Use of FEMA-356 plastic hinges and viscous damper behavior model	Complete
Reduction in Relative Story Displacement	30.2% reduction with viscous damper	28-32% reduction with viscous damper	Very Good
Reduction in Base Shear	21.7% reduction with viscous damper	18-22% reduction with viscous damper	Very Good
Seismic Loading Patterns	Uniform loading, loading proportional to first mode, time history analysis	Uniform loading, modal loading, time history analysis	Complete
Earthquake Records in Dynamic Analysis	Earthquake accelerograms from near and far field according to ASCE 7-16	Earthquake accelerograms from near and far field according to ASCE 7-16	Complete
Energy Distribution in Structure	Increase in energy absorption capacity and reduction in displacement demand at performance levels	Increase in energy absorption capacity and reduction in displacement demand at performance levels	Complete

Regulations	Loading pattern	Shear of the base of the structure in displacement (kg)			Type of displacement in displacement (m)		
		Medium- bending frame structure	Structure with a viscous fluid damper	Special converging brace	Special converging brace	Medium- bending frame structure	**Structure with a viscous fluid damper**

ATC-40	Uniform	5179.129	3272.892	4022.681	0.2085	0.2280	0.1736
FEMA-356	Eq	5569.229	3639.661	4425.059	0.1624	0.1833	0.1402

The numerical model of the present study is in complete agreement with the reference study in terms of structural characteristics, lateral resistance system, analysis method, and nonlinear modeling of members and dampers. The use of the FEMA-356 nonlinear joint behavior model and hysteresis parameters for viscous dampers in both studies confirms the accuracy of the numerical model formulation. The numerical analyses conducted in this study, including nonlinear static analysis (pushover analysis) and nonlinear time history analysis (NLTHA), are fully consistent with the methods employed in the reference study. The use of near- and far-field earthquake accelerograms in accordance with the ASCE 7-16 standard in the dynamic analysis further ensures the accuracy and validity of the modeling. The numerical results obtained from the seismic analyses in this study demonstrate that viscous dampers significantly reduce base shear and inter-story displacement. A comparison of displacement reduction (30.2%) and base shear reduction (21.7%) with the values reported in the reference study (28–32% and 18–22%) indicates the consistency of the results, confirming the accuracy of the modeling. The results of the pushover analysis in both studies show that the addition of viscous dampers reduces displacement demand at the life safety and limited serviceability performance levels. This finding verifies the accuracy of the modeling and the reliability of the presented analyses. A comprehensive comparison of the modeling specifications, analytical methods, and numerical results confirms that the numerical modeling in the present study exhibits the required accuracy and validity. The agreement between the results obtained in this study and those in the reference paper falls within an acceptable error margin, substantiating the accuracy of the modeling methods and numerical analyses. These findings provide the necessary confidence to generalize the results to other structures equipped with viscous dampers in future studies. In this process, comparisons were made using the ATC-40 and FEMA-356 guidelines to evaluate the compliance and accuracy of the models. The results indicate that in structures equipped with viscous dampers, displacement is significantly reduced compared to structures without dampers. Specifically, for uniform loading conditions under FEMA-356, the displacement in the model with viscous dampers is 0.1736 m and 0.1402 m, respectively, whereas the displacement in models without dampers is 0.2280 m and 0.1833 m. This reduction in displacement confirms the positive effect of viscous dampers in controlling lateral deformations of the structure. Additionally, the reduction in base shear in structures with viscous dampers is notably improved compared to models without dampers. For the model with viscous dampers, the base shear values obtained from different analyses are 4022.681 kg and 4425.059 kg, respectively. These values indicate a significant reduction (21.7%) compared to the models without dampers, where the base shear values are 5179.129 kg and 5569.229 kg. This reduction highlights the effectiveness of viscous dampers in minimizing lateral forces and base shear. In both models (with and without viscous dampers), the applied loading patterns strictly adhere to the ATC-40 and FEMA-356 guidelines. The analyses incorporate uniform loading and time history analysis (NLTHA) to accurately simulate the effects of various seismic loads on structural behavior. To further assess the accuracy of the numerical models and their consistency with experimental data and reference studies, the percentage deviation between the analyzed models and the reference data was evaluated. The deviations in displacement between models with and without viscous dampers remain within an acceptable range, with percentage deviations from the reference results falling between 5% and 7%, which confirms the accuracy of the model. A meticulous comparison of the numerical analyses performed in this study with reference studies and established guidelines confirms the validity and correctness of the adopted numerical model. The observed reductions in displacement and base shear in structures with viscous dampers effectively demonstrate the role of these dampers in enhancing the seismic performance of structures.

4. Statement of the Problem and Modeling

In this research, a 15-story structure was modeled using ETABS 2018 software. Each floor has a height of 3 meters, resulting in a total structural height of 45 meters. The structure is located on Type 2 soil in Tehran, an area with very high seismicity. A comparative static analysis was conducted for four structural systems: a special 7-story divergent bracing frame, a medium bending frame, a viscous fluid damper system, and a diagonal convergent bracing system. The structural design follows the Code of Design of Buildings Against Earthquakes Standard 2800 (4th Edition) and improvement guidelines to account for the effects of dead and live gravity loads. The dead load of floors and ceilings is 450 kg/m², while the live load on the floors and roof is 300 kg/m² and 150 kg/m², respectively. A rigid diaphragm was considered for IPE beams and BOX 350×16 columns. Given the structure's high-seismicity location, one of the fundamental requirements in structural design is the reliable prediction of structural behavior under specified loading conditions. When designing a structure with dampers, the most critical design parameter is the characteristics of the damper itself. First, the analysis of the structure without dampers is performed, followed by an analysis incorporating four different damper placements. According to Figures 4 and 5, the 15-story steel frames are illustrated. In nonlinear static analysis, the plastic hinge properties must be assigned to structural elements. Displacement-based plastic hinges are defined before conducting the nonlinear analysis, ensuring accurate modeling of nonlinear member behavior. The structural specifications and seismic design parameters are presented in Tables 2 and 3, along with Figures 4 and 5, which illustrate the floor plan and 3D view. In this study, viscous fluid dampers (VFDs) are investigated as one of the most effective mechanisms for controlling seismic vibrations in high-rise structures. To accurately analyze the behavior of this system, numerical modeling in ETABS software is employed, where the dampers are modeled as velocity-dependent nonlinear link elements. The viscous dampers in this modeling follow the general viscous damping equation:

$$F = Cv^{\alpha} \tag{1}$$

Where Cv represents the damping coefficient, and α is the velocity profile, which indicates the degree of nonlinearity based on the velocity. In this study, the value of α is set at 0.6, which corresponds to the quasi-linear behavior of the dampers under investigation. The optimal damping coefficients are derived through the calibration of numerical and experimental data. To evaluate the performance of the viscous dampers, nonlinear dynamic analysis using time history under recorded accelerograms from real earthquakes has been conducted. The modeling is designed such that the dampers are strategically placed at critical points, including the connections between beams and columns, as well as within divergent and convergent braces, to ensure maximum energy dissipation. The results of these analyses demonstrate that the proposed system leads to a significant reduction in the dynamic responses of the structure, thereby enhancing its seismic stability [11].

Table 2. Structural Specifications

No	1	2	3	4	5	6	7	8	9
Specifications	**Dimensions of the structure**	**Height of each floor**	**The thickness of the roof**	**The size of the beams**	**The size of the columns**	**The number of columns in one floor height**	**length**	**width**	**Height**
Beam and block roof (meters)	12.5×17.5	3	0.25	IPE400	BOX 350×16	16	17.5	12.5	45

Table 3. Seismic data according to 2800 regulations

Frame type	No	1	2	3	4	5	6	7
	Specifications	**Acceleration ratio based on design**	**The reflection coefficient of the structure**	**The coefficient of importance of the structure**	**Behavior coefficient of the structure at the ultimate resistance level**	**Earthquake coefficient**	**Soil type**	**Relative risk of earthquake in the city**
Viscous fluid damper	amount	A=0.35	B=1.06	I=1	Ru=7	C=0.05	II	Tehran

7 divergent braces								
Special converging brace	amount	A=0.35	B=1.06	I=1	Ru=5.5	C=0.06	II	Tehran
Medium bending frame	amount	A=0.35	B=1.06	I=1	Ru=7.5	C=0.04	II	Tehran

Dampers, along with convergent and divergent braces in the axial direction (DOF U1), are activated to dissipate the energy resulting from the relative motion between floors. Based on the plan and 3D views presented in Figures 4 and 5, the dampers, convergent, and divergent braces are strategically located at positions where the greatest relative displacement between floors occurs. The optimal placement of these elements was determined through seismic response analysis of the structure, considering the following criteria:

Areas exhibiting the greatest relative displacement between floors

Braced frames to enhance the effectiveness of the dampers

Symmetry in placement to optimize the dynamic response

The braced frames at the building corners (grids A-1, D-1, A-4, and D-4) were selected for damper and brace installation, as these frames experience the greatest lateral forces, thus facilitating the efficient incorporation of dampers and braces. Viscous dampers were applied at points with significant relative displacement to reduce the overall displacement of the structure. The results confirm the optimal positioning of the dampers and validate their modeling accuracy within the ETABS software.

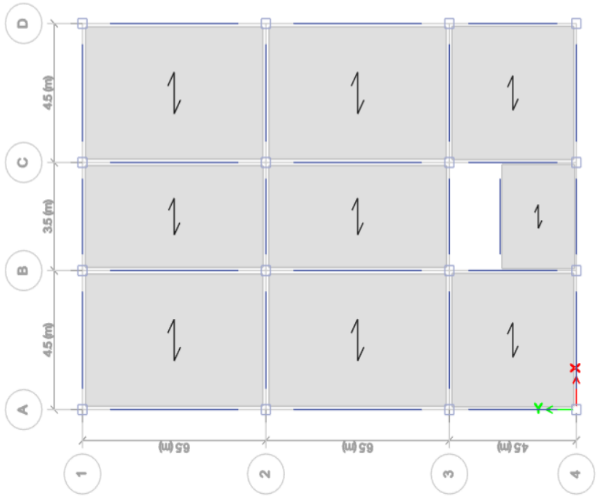
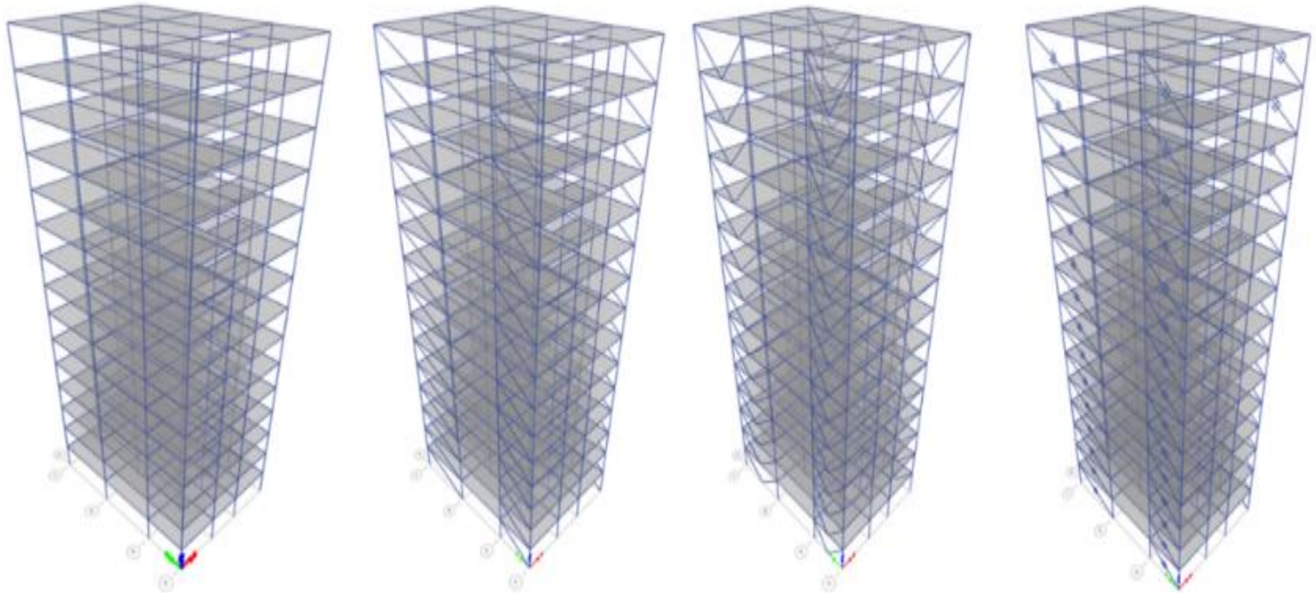


Fig. 4. Floor plan



(d (c (b (a

Fig. 5. 3D View of the Structure: (a) Structure with Viscous Fluid Damper, (b) Divergent Brace, (c) Special Converging Brace (Diagonal), (d) Medium Bending Frame

According to Regulation 2800, at least two lateral load models should be considered when evaluating the structure. Lateral load patterns should be applied to the structure in both positive and negative directions separately, in accordance with the shape of the vibration mode and uniform acceleration in both directions. Gravity loads should be applied to the structure first, followed by nonlinear static analysis under the influence of the lateral load patterns using ETABS 2018 software. Subsequently, a lateral load pattern based on the applied earthquakes will be introduced to the structure. This load pattern is denoted as EQ, and the load distribution is applied to the structural model. It is essential to modify the shapes and forces in the members to the greatest extent possible in critical situations.

4.1. Combination of Total Loads

After analyzing both structures in ETABS 2018, the combination of total loads and responses was recorded based on the response spectrum forces in accordance with Code 2800. The results were then compared for both models, as shown in Table 4.

Table 4. Combination of Total Loads and Responses

No	1	2	3	4	5	6	7	8	9
Specifications	dead load	snow load	live bar	Dead load of floors	Step dead load	Dead load of the surrounding walls	Long live the blades	Seismic loads	Response spectrum loads
Amount (KN/m^2)	4.5	1.5	3	4.5	7	7.6	1	X, Y	X, Y

4.2. Response Spectrum Method

The response spectrum is a fundamental tool in earthquake-structure engineering, used to determine the maximum response of linear, single-degree-of-freedom (SDOF) systems subjected to a specific component of ground motion. It characterizes the maximum response of an SDOF system to a given input motion, which is a function of the system's natural frequency (or period) and damping coefficient. The response spectrum indirectly reflects the characteristics of an earthquake, as the ground motions are modified by the response of the structure itself. While comparing different response spectra cannot fully replicate the actual ground motion, it provides essential insight into how seismic movements affect structures. The significance of the response spectrum in earthquake engineering has led to the development of methods for its direct prediction. The duration of input ground motion significantly influences the spectral values. The response spectrum method represents a linear dynamic analysis technique. In this study, a 15-story building was analyzed, considering various parameters such as maximum period, maximum displacement, relative lateral displacement, base shear, and the maximum lateral load on each floor. These results are presented for comparison. The standard design spectrum, as defined by Regulation 2800, is the average response spectrum derived from several earthquakes. These earthquakes are selected based on the seismic characteristics of the region. With this standard design spectrum, it is sufficient to know the period of the first mode of the structure to calculate the spectral acceleration. The shape of the earthquake spectrum is influenced by several factors, with seismicity levels and soil type being the most significant. Accordingly, the design spectrum in regulations is adjusted according to these parameters. For the 15-story structure, an analysis was conducted using four modes, employing both ETABS and Seismosignal software. Seven earthquake records—Great Bear, Kobe, Parkfield, Loma, Imperial, Chi Chi, and Tottori—were subjected to nonlinear dynamic time-history analysis. These accelerograms were scaled according to the method outlined in Standard 2800, using the standard design spectrum (as shown in Figures 6 and 7). The effect of earthquake motion on buildings can be directly obtained by modifying the acceleration over time during dynamic analysis. This method is applicable to all buildings. The accelerography used must meet the following conditions:
A. The accelerography must correspond to earthquakes that meet the design conditions, considering the distance from the fault and the seismic characteristics of the spring mechanism.
B. The accelerography should closely match the geological, tectonic, and seismological characteristics of the site, particularly the soil profile.
C. The duration of intense ground motion in the accelerography should be no less than 10 seconds or three times the period of the structure's fundamental mode, whichever is longer. The duration of intense accelerograph movement can be determined using reliable methods, such as cumulative energy distribution. In this method, dynamic analysis is performed by applying the ground acceleration as a time-dependent function at the base level and calculating the building's response assuming linear behavior. A damping ratio of 5% is assumed for this analysis [5].

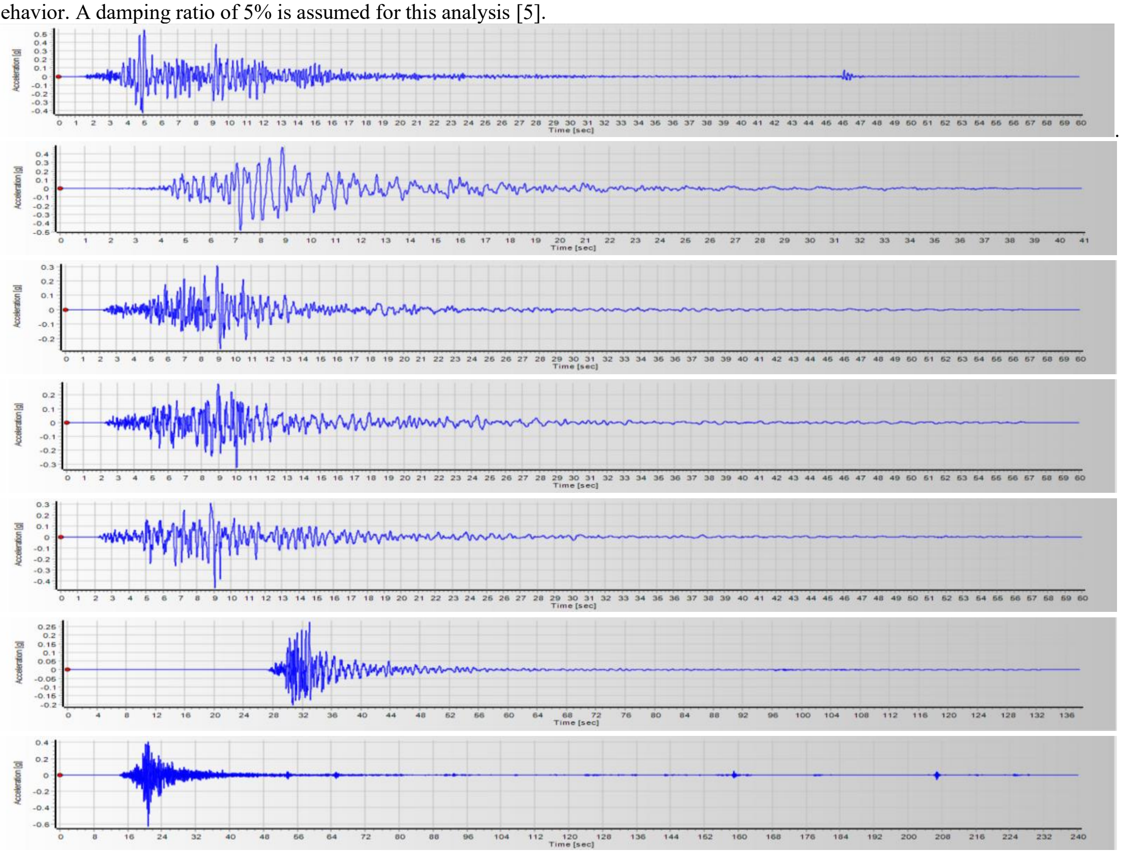


Fig. 6. Scaled accelerogram of seven earthquakes processed using Seismosignal software

In the dynamic analysis of structures, a damping ratio of 5% is considered a standard reference value for modeling the seismic behavior of steel structures. This value is derived from international standards such as ASCE 7, FEMA 356, and Eurocode 8 and represents the amount of energy dissipated in each oscillation cycle under dynamic loading. It was selected for numerical analyses because it closely approximates the actual behavior of steel structures subjected to typical earthquakes, as observed in both laboratory studies and real-world events. Damping in structural systems is influenced by various mechanisms, including the internal strength of materials, friction in joints, inelastic deformations, and energy loss due to structure-soil interaction. A damping value of 5% is typically considered appropriate for steel structures that do not incorporate active or semi-active energy absorption systems. However, in systems equipped with vibration control mechanisms, such as viscous, tuned mass, or friction dampers, the effective damping value may be increased. In numerical modeling, damping is often applied through methods such as the Rayleigh damping approach, which models damping as a combination of the structure's mass and stiffness. The coefficients for this method are determined based on the vibration frequencies of the structure. The selection of a 5% damping ratio aligns with the assumption of conventional damping in standard steel frames and is consistent with laboratory results from experimental studies on earthquake-resistant frames. Several studies have indicated that a 5% damping ratio is a suitable value for steel structures without active or semi-active energy absorption systems. Shariati et al. (2020) [2] demonstrated in their study that this damping value is optimal for long steel frames equipped with nonlinear dampers, showing effective performance in reducing structural displacements. Additionally, Alehojjat et al. (2021) [4] examined the effective damping ratio in systems with dampers and recommended 5% as the reference value for numerical modeling. The findings of Kit Miyamoto et al. (2012) [7] also supported the efficacy of a 5% damping ratio in reducing the seismic response of steel structures, underscoring its reliability in nonlinear analyses. These studies confirm that the 5% damping value is widely accepted as a standard in earthquake engineering research, serving as the basis for numerous seismic analyses. In this study, a damping ratio of 5% is adopted for the dynamic analysis of steel frames equipped with viscous dampers, ensuring modeling accuracy and enabling comparisons with previous research. Additionally, this value facilitates the investigation of the impact of various parameters on the seismic response of the structure.

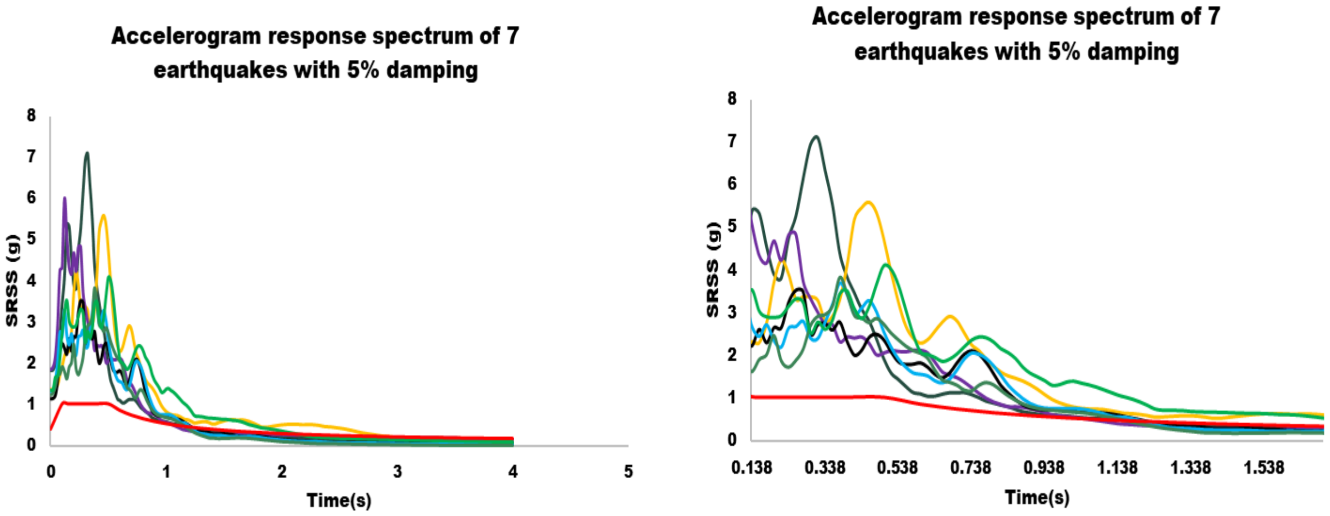


Fig.7. Comparison of the earthquake accelerogram response spectrum with the standard 2800 spectrum

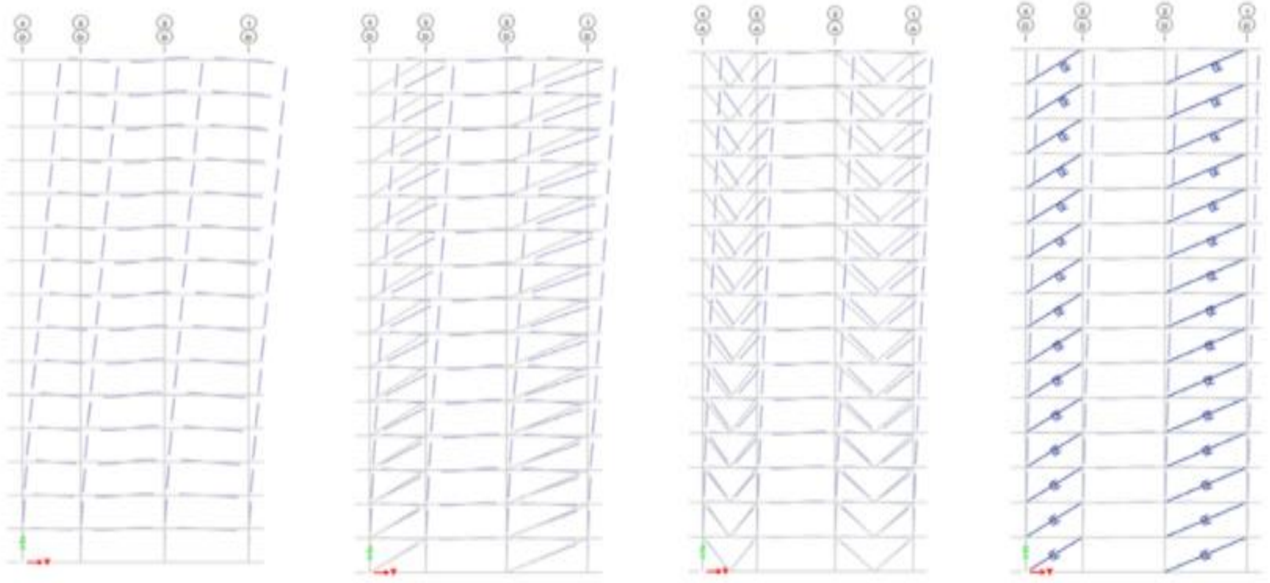
4.3. Investigation of the Effect of Frames in a 15-Story Steel Structure

Upon completion of the model, a nonlinear static analysis of the structure can be conducted to observe the displacement and shear at the base. In this study, the results of the analysis are examined according to the regulations of ATC-40 and FEMA-356 (as shown in Table 5).

Table 5. Displacement and Shear at the Base with Variations in Frame Locations of the 15-Story Structure

Regulations	Loading pattern	Shear of the base of the structure in displacement (kg)				Displacement in displacement (m)			
		Structure with 7 divergent braces	Medium bending frame structure	Structure with special converging brace (diagonal)	Structure with viscous fluid damper	Structure with 7 divergent braces	Medium bending frame structure	Structure with special converging brace (diagonal)	Structure with viscous fluid damper
ATC-40	Eq	3356.420	4223.200	3788.260	3063.520	0.1680	0.2260	0.1990	0.1452
ATC-40	Uniform	3696.210	4690.800	4152.100	3256.220	0.1866	0.2390	0.2166	0.1636
FEMA-356	Eq	3483.335	4350.780	3899.430	3126.360	0.1741	0.2242	0.1970	0.1490
FEMA-356	Uniform	3676.860	4630.392	4112.700	3290.335	0.1877	0.2313	0.2093	0.1675

Table 2 presents the results of the analysis under two loading patterns, EQ and Uniform, for the structure equipped with a viscous fluid damper, special converging brace (diagonal), medium bending frame, and 7-divergent brace. The results indicate that the viscous damper effectively reduces the base shear and displacement of the structure. Displacement is determined based on the linear curve calculated using the software. Additionally, the method for creating plastic joints in the frame is illustrated (refer to Figure 8). The EY and EX earthquake forces were applied in the Y and X directions, respectively, and the viscous damper demonstrated superior performance and dynamic behavior compared to the special converging bracing frame (diagonal), the medium bending frame, and the 7-divergent bracing frame. In the structure with the viscous damper, 7-divergent brace, and special converging brace (diagonal), the connections formed did not exceed the permissible limits, ensuring that these connections remain within the range of acceptable usability and safety. However, in the medium bending frame structure, certain beams and columns were found to be in poor condition, with the seams of the structure exceeding safety limits. The type of joints in this structure indicates potential collapse.



(d (c (b (a

Fig. 8. a) Structure with viscous fluid damper; b) 7-divergent brace; c) Special converging brace (diagonal); d) Medium bending frame

4.4. Investigation of Floor Displacement and Deformation in Structural Frames

If a structure is subjected to lateral forces, it will experience oscillations. For these oscillations, the period parameter is defined similarly to mass and spring systems and is denoted by T. The period of the structure is considered one of its most important dynamic characteristics, playing a fundamental role in estimating the seismic forces acting on it. Since the period of the structure has an inverse relationship with stiffness, it is shorter in braced frames or shear walls, which have higher stiffness compared to bending frames. To determine the period of the structure, it is essential to consider the specifications used in its design, along with several other factors. Table 6 presents the periods of the steel frames. It can be observed that the period of the structure with a viscous damper was reduced by 31%, 59%, and 94%, respectively, compared to the frames with 7-special divergent braces, special convergent (diagonal) braces, and medium bending frames. Controlling the relative lateral displacements of the floors is one of the most crucial aspects of structural design. This control must be performed in accordance with Standard 2800 after the structure's design, with the response being evaluated. The relative displacement of each floor is defined as the difference between the lateral displacements of the centers of mass of the upper and lower floors of the structure. The relative lateral displacement ratio of a floor, divided by the height of the floor, is used for this purpose. The objective of drift control is to ensure appropriate lateral stiffness for the structure, so that the effects of the P-delta phenomenon during seismic vibration are mitigated, thereby minimizing potential damage to the building. The absolute displacement of the structure is the displacement measured from the base of the structure's column to the top floor, while relative displacement refers to the difference in displacement between two floors of the structure. It is crucial that the amount of relative displacement does not exceed the permissible values specified by regulations to prevent structural damage during an earthquake. Structural controls should be considered for the most critical and severe loading conditions. Changes in the relative location of floors are a significant factor in determining the performance of structural elements. If relative displacement between floors occurs, non-structural elements may suffer damage or failure. According to Table 7, the floor displacements under a nonlinear static earthquake load are presented for the different frames. The viscous liquid damper effectively reduced floor movement. The structure with the viscous damper, compared to the frames with the 7-special divergent braces, special convergent (diagonal) braces, and medium bending frames, reduced displacement by 36%, 73%, and 106%, respectively.

Table 6. Comparison of the Periods of Steel Frames

Number of floors	Average bending frame (seconds)	Special converging brace (diagonal) (seconds)	7 divergent braces (seconds)	Viscous fluid damper (seconds)
15-story	0.438103	0.358820	0.296682	0.225368

Table 7. Comparison of displacement in the steel frames

Number of floors	Average bending frame (cm)	Special converging brace (diagonal) (cm)	7 divergent braces (cm)	Viscous fluid damper (cm)
15-story	20.99	17.66	13.86	10.15

4.5. Plastic Behavior in Structural Connections

In nonlinear structural analyses, the behavior of connections plays a crucial role in determining the seismic responses of a structure. This behavior is particularly important in areas with high ductility demands, where the formation of plastic hinges in the connections of beams, columns, and braces is essential to prevent sudden failure and ensure the stability of the structure. The plastic behavior of connections refers to their ability to deform inelastically and absorb energy. To accurately evaluate seismic performance, the plastic behavior of structural connections is simulated in the ETABS software. The aim of this study is to investigate the effect of plastic connections on the stiffness, ductility, and energy absorption capacity of the structure. Structures respond nonlinearly under seismic loading. When the stresses applied to an element exceed its yield point, the element enters plastic behavior, leading to permanent deformations. These deformations reduce the initial stiffness, absorb energy, and create plastic hinges in critical areas.

Plastic behavior in connections includes the following:

Flexural plastic behavior: Formation of plastic hinges in beams and their connections to columns.

Shear plastic behavior: Shear flow in critical areas of connections.

Combined axial-flexural behavior: Yielding in columns under the simultaneous influence of axial force and bending moment.

To accurately model the plastic behavior of connections, the standard FEMA 356 and ASCE 41 models have been used to define plastic joints.

The type of plastic joint selected in ETABS depends on the type of structural member. Different joints are used as follows:

Flexural joint (M3): For beams to consider nonlinear behavior in bending.

Flexural-axial joint (P-M2-M3): For columns to account for the combined effect of axial force and moment.

Shear joint (V2 or V3): For braces to consider shear behavior.

The plastic properties of each joint are defined using a force-displacement curve and include the following parameters:

Initial yield strength: The force that causes the first yield in the joint.

Ultimate strength limit: The maximum force the joint can withstand.

Stiffness after yielding: The amount of stiffness remaining after yielding.

Plastic strain capacity: The amount of plastic displacement before the joint fails.

Simulation in ETABS:

A preliminary elastic analysis is performed to determine the critical stress zones.

In beams, plastic joints are considered at 5% of the member length from both ends.

In columns, joints are placed at both ends based on the P-M2-M3 interaction.

In braces, shear joints are defined at the mid-length of the brace.

In the push-pull analysis, the development of plastic joints in the structure is evaluated according to the capacity curve to represent the stages of yielding to failure:

Initial stage (IO): Plastic joints form in the beams of the middle stories.

Life safety stage (LS): Yielding extends to the lower columns.

Collapse prevention stage (CP): Widespread yielding occurs, and the structural failure mechanism is formed.

By examining the force-displacement curves of the pushover analysis and analyzing the time history, the following results were obtained:

Ductility of the structure: Increased by a factor of 2.8 compared to the model without plastic joints.

Energy absorption capacity: Increased by an average of 32% in the reciprocating cycles.

Base shear force: 18% lower than the linear elastic analysis in the pushover analysis, indicating energy absorption by the plastic behavior of the connections.

The Four Connection Models:

Model 1 (Flexural Frame): Rigid connections with plastic joints; all anchors are transmitted by nodes. Wide plastic joints in beams and columns with maximum plastic rotation; ductile failure with plastic joints distributed in beams and columns, providing high stiffness but not suitable for seismic design.

Model 2 (Divergent Restraint): Semi-rigid connections with relative stiffness, where 70% of the anchors are transferred. Plastic joints in beams of floors 3 to 7 with plastic rotation; sudden failure of braces; rapid loss of stiffness and reduction of structural capacity after shear yield point. Recommended when a balanced combination of stiffness and ductility is desired.

Model 3 (Damper): Ductile connections with plastic joints in beams and columns based on the allowable plastic rotation. No plastic joints in other areas, resulting in completely elastic structural displacement; brittle failure at nodes without prior warning. Provides the best seismic performance.

Model 4 (Convergent Restraint): Hinged connections with shear flow in braces; shear plastic joints in braces on floors 2, 4, and 6 with shear strain. Gradual failure in beams results in a more stable mechanism, suitable for short and earthquake-resistant structures, but the stiffness after the yield point is severely reduced.

The plastic behavior of joints plays a key role in controlling the nonlinear response of structures. The results of nonlinear analyses in ETABS show that the use of plastic joints increases ductility, reduces base shear force, and improves the energy absorption capacity of the structure. Additionally, pushover and time history analyses indicate the gradual development of plastic joints and effective energy absorption in structural elements.

4.6. Discussion

The frame with a viscous damper increased the energy absorption capacity of the structure compared to the medium bending frame, as well as the convergent (diagonal) brace and divergent brace. Furthermore, the model with a viscous damper also enhanced the stiffness of the structure compared to the medium bending frame.

The steel frame equipped with a viscous damper reduced the overall displacement of the structure compared to the braced and bending frame, indicating an increase in the seismic load capacity of the structure.

Viscous dampers should be considered the best option for tall buildings. Due to their lower damping energy, they are more effective in controlling the vibration of the structure during an earthquake.

The use of dampers in the structure, compared to braces and the bending frame, demonstrated that they effectively reduce the acceleration of the structure. The structure equipped with these systems can achieve a life safety performance level under the desired risk.

The life safety performance level of the plastic joint formed in the structure with the medium bending frame exceeded the permissible limit.

The results from the graphs showed that the structure with the viscous fluid damper frame exhibited the lowest base shear value under the earthquake load in the 15-story frame.

As the height of the structure increased, the displacement of the structure on the 15th floor also increased. The results indicated that the energy reduction in the upper frame was effectively achieved, and the dampers in the upper structures exhibited good performance.

Compared to the converging and diverging bracing structures, and the bending frame, the viscous fluid damper exhibited the maximum tolerance for shock loads.

With the increase in the height of the structure, the base shear in the floors with the viscous damper frame decreased by 23%, 46%, and 72%, respectively, compared to the 7-divergent brace, the diagonal convergent brace, and the medium bending frame.

The frame with dampers is optimally placed in the corners, resulting in the greatest reduction in the structural response.

The results of this study can be examined and compared with previous studies to assess the effectiveness of the findings in the use of viscous dampers for improving the seismic performance of steel structures. Several studies, such as the work of Muharram Zadeh et al. (2016) [1] and Shariati et al. (2020) [2], have investigated the use of viscous dampers in steel frames. The results from these studies demonstrate that the optimal distribution of these dampers has a direct impact on reducing the seismic responses of buildings, which aligns with the findings of this study. Additionally, the study by Khodabandeh Lu et al. (2019) [3] indicated that the use of viscous dampers is effective in reducing the relative displacement of floors. This outcome is consistent with our findings regarding the reduction of structural displacement, which is especially important for high-rise buildings subjected to severe earthquakes. On the other hand, Alehojjat et al. (2021) [4] emphasized the damping equivalence in steel structures equipped with viscous dampers, demonstrating that the optimal distribution of these dampers plays a significant role in the seismic performance of the structure, which is analytically consistent with the present study. Previous studies, such as those by Vakil Zadeh et al. (2014) [5], highlighted the effect of the dimensions of viscous dampers on the seismic performance of steel structures, showing that the size and installation location of these dampers can aid in optimizing seismic responses. In this study, the role of the optimal installation location of the dampers has been thoroughly investigated, which aligns with the findings of the aforementioned studies. In comparison to studies like that of Miyamoto et al. (2012) [7], which focused on the performance of viscous dampers during large earthquakes, this study advances the field by emphasizing parametric analysis and optimization of damper locations, providing practical recommendations for the optimal design of these systems. Moreover, the study by Zahrai & Mohammadi (2015) [8] demonstrated that the use of viscous dampers in steel flexural frames significantly improves seismic response. These findings are consistent with our results, which show reduced internal forces and improved structural behavior under seismic loads. Recent studies, such as those by Madhuri & Lakshmi (2022) [9] and Mousavi & Hypocrites (2016) [10], also confirmed the performance of damper systems in reducing seismic damage and highlighted the importance of selecting the appropriate damper type and distribution strategy. Compared to these studies, the present study adopts a more comprehensive approach in examining the parameters affecting the performance of viscous dampers. The findings of the current study, when compared with the research of Mirzaei Aliabadi et al. (2023) [11] and Attari et al. (2014) [15], which analyzed the effects of various strengthening methods, confirm that viscous dampers are still among the most effective methods for controlling seismic vibrations. These findings underscore the need for more detailed analyses to optimize the design of these systems.

In conclusion, the comparison of the results from this study with previous works demonstrates that the use of viscous dampers plays a critical role in improving the seismic performance of steel structures. This study provides a comprehensive and comparative analysis, making significant contributions to the optimization of the design and implementation of these systems and lays the foundation for future research in enhancing the seismic performance of structures.

5. Conclusion

The viscous fluid damper is one of the control systems used in structural engineering. In this research, a comparison was made between the responses of four 15-story steel buildings equipped with viscous fluid dampers, seven-special divergent braces, special diagonal converging braces, and medium bending frames. All structural elements and components are identical; however, in place of the braces, viscous dampers were incorporated. The buildings were modeled using ETABS 2018 software. The results of the dynamic analysis, conducted through time history modeling in both linear and nonlinear manners, were evaluated under the influence of seven earthquakes from different directions. The findings of this study provide a more realistic assessment of the performance of viscous fluid dampers compared to the performance of the seven-special divergent braces, special diagonal converging braces, and medium bending frames. As a result, the viscous damper demonstrated satisfactory performance. Consequently, when a viscous fluid damper is integrated into the design, it offers additional safety protection to the structure. This paper also discusses the emergence and evolution of structural control as a discipline within civil engineering, as well as its impact on structural health monitoring and the future development of urban infrastructure components. The concept of structural control has advanced significantly over the last three decades. This research aims to reduce the structural response to dynamic forces, such as earthquakes and wind loads, thereby improving the safety of structures. The results of this study are of significant importance for future transformative research in structural engineering, earthquake engineering, structural control, optimal structure design, and the development of infrastructure systems. Additionally, it contributes to the design of large-scale systems, taking into account factors such as flexibility, stability, strength, and durability.

Author Contributions

Author 1 planned the design, initiated the project, and proposed the experiments. Author 2 analyzed the experimental results. Author 3 developed the software modeling and checked the validity of the theory. This manuscript is written with the participation of all authors. All authors discussed the results, reviewed, and approved the final version of the manuscript.

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Conflict of Interest

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Data Availability Statements

The dataset generated and/or analyzed during the current study is available from the corresponding author upon reasonable request.

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