buildings

Article

Effect of U-Shaped Metallic Dampers on the Seismic Performance of Steel Structures based on Endurance-Time Analysis

Farhad Farajiani [1,*], Farzaneh Elyasigorji [1], Sina Elyasigorji [1], Mohammad Javad Moradi [2] and Visar Farhangi [3,*]

[1] Department of Civil and Environmental Engineering, University of Wisconsin-Milwaukee, Milwaukee, WI 53211, USA
[2] Department of Civil and Environmental Engineering, Carleton University, Ottawa, ON K1S 5B6, Canada; mjmoradi@cmail.carleton.ca
[3] Department of Civil Engineering, Construction Management, and Environmental Engineering, Northern Arizona University, Flagstaff, AZ 86011, USA
* Correspondence: authors: farajia2@uwm.edu (F.F.); visar.farhangi@nau.edu (V.F.)

Abstract: Seismic performance of steel moment-resisting frames is investigated through the incorporation of U-shaped metallic dampers. The primary objective is to assess the effectiveness of these dampers in mitigating seismic responses by utilizing various analysis techniques. Two representative structural configurations (5 and 10-story) are studied in both damped and undamped states to reveal the impact of dampers on seismic response reduction. The study utilizes the endurance time analysis (ETA) method, known for its efficiency in evaluating structural seismic performance. To validate the analysis results, a benchmark comparison is made through nonlinear time history analysis (NTHA). Incremental dynamic analysis (IDA) is also conducted to assess structures' intensity measures with respect to their damage intensity index. The findings demonstrate that U-shaped metallic dampers substantially reduce inter-story drift and story shear forces. Importantly, a close alignment between the results obtained from ETA and NTHA underscores the reliability of the former in assessing seismic performance with supplemental damping devices.

Keywords: U-shaped metallic damper; endurance time analysis; nonlinear time history analysis; Seismic performance

Citation: Farajiani, F.; Elyasigorji, F.; Elyasigorji, S.; Moradi, M.J.; Farhangi, V. Effect of U-Shaped Metallic Dampers on the Seismic Performance of Steel Structures based on Endurance-Time Analysis. *Buildings* **2024**, *14*, 1368. https://doi.org/10.3390/buildings14051368

Academic Editor: Xavier Romão

Received: 19 March 2024
Revised: 29 April 2024
Accepted: 2 May 2024
Published: 10 May 2024

1. Introduction

The built environment is significantly and repeatedly threatened by earthquakes, which also sadly claim human lives and severely damage buildings and infrastructures. Designing and building structures that can withstand earthquakes is essential for protecting residents and reducing financial losses in seismically active areas. At present, structures designed using conventional structural design codes dissipate the forces from seismic events by nonlinearizing the structural elements. Non-linearity of structural elements causes damage to these elements and, therefore, damage to existing structures under severe earthquakes is inevitable. This has led researchers in the field of civil engineering to research and present new structural systems that are able to withstand severe seismic forces on the structure without damaging the main components of the structure. Generally speaking, the natural damping of the structures dissipates a portion of the incoming seismic energy, while the primary structural system including beams, columns, and walls absorbs the majority of it. In this regard, supplemental dampers were utilized to reduce the damage of the main structural components as well as controlling the whole structure responses. Dampers, as energy dissipation devices, will absorb the majority of the seismic energy, preventing or reducing such damages. A structural design approach incorporating these systems is now widely accepted and regularly used in civil engineering. The four main categories of structural energy dissipation systems are passive, active, semi-active, and hybrid systems [1–4]. A passive damper is easier to build and install than an active or semiactive damper. Passive energy dampers are regarded as a cutting-edge and efficient structural engineering technique that enhances the functionality of structures. Using energy dampers has a number of significant benefits, including structural stability under seismic stresses and the fast repair or replacement of specific structural sections following an earthquake [5].

Considering the passive structural control systems, metallic dampers, also known as hysteretic dampers, have been extensively researched in the past to improve structural performance by lowering seismically induced structural damage. These dampers are specially designed to act as passive energy dissipation devices. In this regard, metallic dampers have been used largely in moment frames to eliminate (or at least mitigate) inelastic behavior in beams and columns and reduce inter-story drifts [6]. Metallic dampers are among the most popular passive energy dissipation devices due to their cost-effective production, consistent hysteresis performance, resistance to changing temperatures, dependability, and impressive energy dissipation capacity [7]. The use of metallic yielding dampers has always been considered by researchers due to their high energy absorption and, at the same time, its cost-effectiveness. In the event of powerful earthquakes, metallic dampers are designed to dissipate energy through plastic deformations [8]. Plastic deformations help the yielding dampers dissipate energy. In this regard, the geometry of the dampers has a significant impact on how plastic deformations are distributed throughout these devices [9]. Metallic dampers can be utilized to increase the seismic resilience of steel moment-resisting frames. Since the dampers are displacement-dependent devices, they might fail under severe earthquakes when the maximum displacement is achieved [10].

Kelly et al. used yielding metal dampers for the first time to reduce the structural seismic responses [11]. Later, other researchers have tried to reduce the seismic responses of structures by using different types of yielding metal dampers and thus reduce the damage caused by seismic events. ADAS, TADAS, hourglass, BRB, and slit are among some of the metallic dampers [12–16]. Metallic dampers were also successfully employed in vertical mass isolation systems to reduce the responses of structures during seismic events [17]. Additionally, the utilization of a shape memory alloy U-shaped damper has also been proved to be effective in terms of reducing residual deformation and enhancing seismic performance of the structures [18].

Performance-based seismic design represents a paradigm shift in the field of structural engineering, offering a proactive and dynamic approach to mitigating the risks associated with seismic events. In contrast to conventional code-based design methods that primarily focus on ensuring life safety, performance-based design places a strong emphasis on achieving specific performance objectives, tailored to the unique needs of each structure. This approach accounts for a wide range of earthquake scenarios, from minor ground motion to catastrophic events, and assesses how a structure will behave under various levels of seismic intensity. By incorporating advanced analysis techniques, hazard assessments, and iterative design adjustments, performance-based seismic design not only enhances structural resilience but also optimizes cost-effectiveness. Among the primary challenges in estimating the seismic demand and capacity of non-linear structural systems and assessing their seismic performance during large earthquake occurrences, are computational complexity and high computing costs [19]. The present performance-based seismic evaluation approach can be computationally demanding since it necessitates a large number of time history analyses, each of which necessitates time-consuming post-processing of data [20]. Although time history analyses are always considered and used by researchers due to their high accuracy in evaluating the performance of structures that have been subjected to seismic forces, these analyses have disadvantages such as being time consuming due to the large volume of calculations. For this reason, alternative analyses that have the ability to determine and evaluate the seismic performance of structures with high accuracy; close to time history analyses are considered and developed by researchers. Endurance time is among the simplified analysis methods to solve the high computational cost of the conventional techniques. For the first time, Estekanchi et al. devised the endurance time approach. This approach relies on accelerograms characterized by a linear increase in intensity over time [21]. The endurance time approach is a time history-based method for seismic evaluation of structures that uses increasing dynamic stimulation as the loading function [22]. When using the endurance time method, structures are subjected to a specially created intensifying ground acceleration function, and their performance is assessed based on how they react to different levels of excitation [23]. In comparison to complete nonlinear response-history assessments, a range of similar intensities can be covered in a single numerical or experimental simulation, greatly lowering the computational load [23]. When using the endurance time method, structures are subjected to a specially created intensifying ground acceleration function, and their performance is assessed based on how they react to different levels of excitation. In comparison to complete nonlinear response history assessments, a range of similar intensities can be covered in a single numerical or experimental simulation, greatly lowering the computational load [23].

In this paper, the performance of steel moment-resisting frames retrofitted with U-shaped metallic dampers was evaluated through the utilization of nonlinear time history and incremental dynamic analyses. To assess the effectiveness of the dampers, the frames with and without dampers were analyzed. Although nonlinear time history analysis is known for its reliability, it is also acknowledged for its time-consuming nature. In a world where seismic events pose a persistent threat to infrastructure and human safety, finding innovative ways to enhance the seismic performance of structures while simultaneously optimizing computational resources is of paramount importance. Consequently, a new analysis method called endurance time analysis was also employed as an alternative, offering a quicker evaluation. The results of both analysis methods were compared to ensure the reliability of the endurance time analysis results in assessing the seismic performance of these structures.

To assess the performance of the U-shaped metallic damper, a finite elements analysis was conducted on a model and the results of the analysis were verified by the experimental data. The results showed that the U-shaped metallic damper can be subjected to large deformations without extensive strength reduction which proves the effectivity of the damper for seismic performance enhancement of the structures.

2. U-Shaped Metallic Damper

U-shaped metallic dampers represent a noteworthy advancement in enhancing the seismic performance of steel moment-resisting frames. These innovative devices are strategically integrated within the frame structure to mitigate the detrimental effects of seismic forces. U-shaped metallic dampers consist of high-strength steel elements formed into a U-shape, and they are designed to dissipate seismic energy through controlled yielding and plastic deformation during an earthquake event. Their unique geometry and material properties enable them to efficiently absorb and dissipate energy, thereby reducing the magnitude of lateral displacements and inter-story drifts experienced by the frame. This not only enhances the structural integrity of the steel moment-resisting frame but also minimizes damage to non-structural components and improves occupant safety. The incorporation of U-shaped metallic dampers presents a promising avenue for optimizing the seismic resilience of steel moment frames, making them a valuable asset in earthquake-prone regions and a subject of extensive research and development in structural engineering.

Previous research suggested that U-shaped metallic dampers may absorb energy during high displacements without losing strength or stiffness, making them a potential complement to lateral load-bearing systems [24].

Geometrical characteristics and material yield stress are what determine U-shaped metallic damper's cyclical behavior. Additionally, the geometry, number, and cross-section of the U-shaped dampers may be simply changed to alter the performance of these devices, making them an efficient solution that satisfies a variety of seismic isolation design requirements in high and moderate seismic zones [25].

According to the testing and evaluation conducted by Dolce et al. [26], each curved steel member with dimensions of 100 mm by 10 mm and a bending angle of 50 mm was considered for the cross-section. In this experiment, the U-shaped damper exhibited an initial stiffness of 2,000,000 kgf/m and a yield force of 9247 kgf. These values pertained to the case where a pair of curved steel plates was used. Using the provided initial stiffness and yield strength values for the damper, as well as Equation (1), one can calculate the yielding displacement of the damper.

$$\Delta_y = \frac{k}{F_y} \quad (1)$$

where Δ_y is the displacement at the yielding point, k is the initial stiffness' of the damper, and F_y is the yielding strength of the damper. It was also shown that the U-shaped damper exhibited a bilinear force-displacement behavior with the plastic stiffness being approximately 0.01 of the initial stiffness. The schematic installation of the U-shaped metallic damper in steel structures is shown in Figure 1.

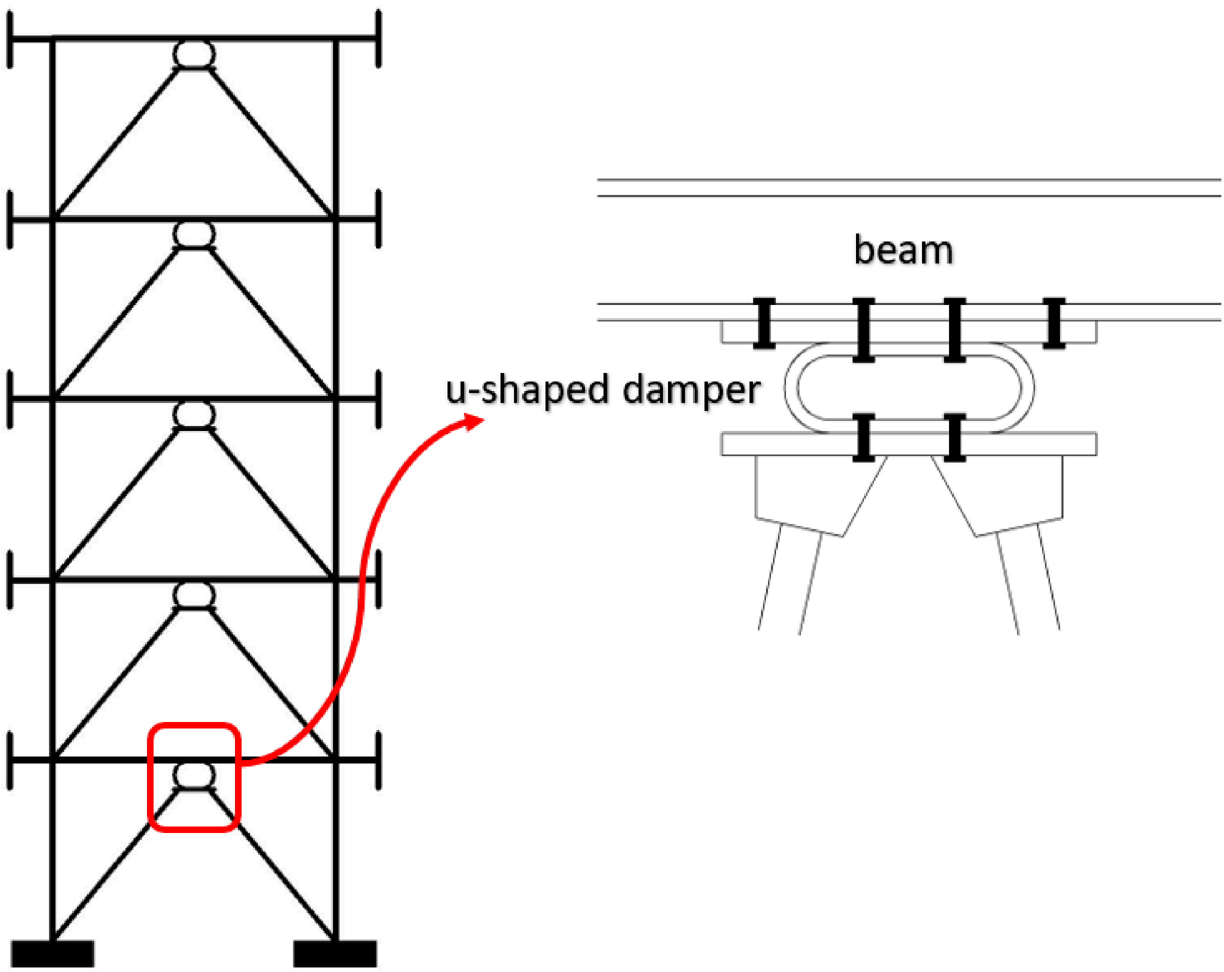

Figure 1. Schematic installation view of U-shaped damper.

The U-shaped metallic damper was comprehensively investigated using nonlinear finite element analysis in ABAQUS. The damper model was constructed using solid elements (C3D8R) and incorporated a nonlinear isotropic material model to accurately capture its behavior. The material properties, outlined in Table 1, were incorporated into the model. Subsequently, the damper underwent cyclic loading [24], enabling a thorough examination of its hysteric behavior. The bottom of the damper was fixed through all six degrees of freedom, and the load was applied to the top face of the damper in the horizontal translational direction. It should be noted that the other five degrees of freedom at the top face of the damper were fixed. Additionally, von-Mises stresses, as presented in Figure 2, indicated that the damper effectively resisted large deformations without experiencing significant strength reduction. The cumulative enclosed area of the hysteretic loops can be used to assess the energy dissipation mechanism of the damper. Even after significant inelastic deformation, the hysteretic curves displayed completely balanced behavior for both tension and compression forces. This suggests that the U-shaped metallic damper possesses the capability to dissipate seismic energy efficiently. Consequently, the primary structural elements remain safeguarded, experiencing minimal damage, thereby underscoring the damper's efficacy in enhancing the seismic resilience of the structure.

Table 1. Utilized section properties (units: mm).

Member ID.	Section	Member ID.	Section	Damper ID.	k (kN/m)	F_y (kN/m^2)
C1	TUBO250X250X15	G2	IPE330	U1	19,613	90
C2	TUBO200X200X15	G3	IPE400	U2	39,226	180
C3	TUBO300X300X25	G4	IPE450			
C4	TUBO250X250X20	B1	TUBO80X80X10			
G1	IPE360	B2	TUBO100X100X10			

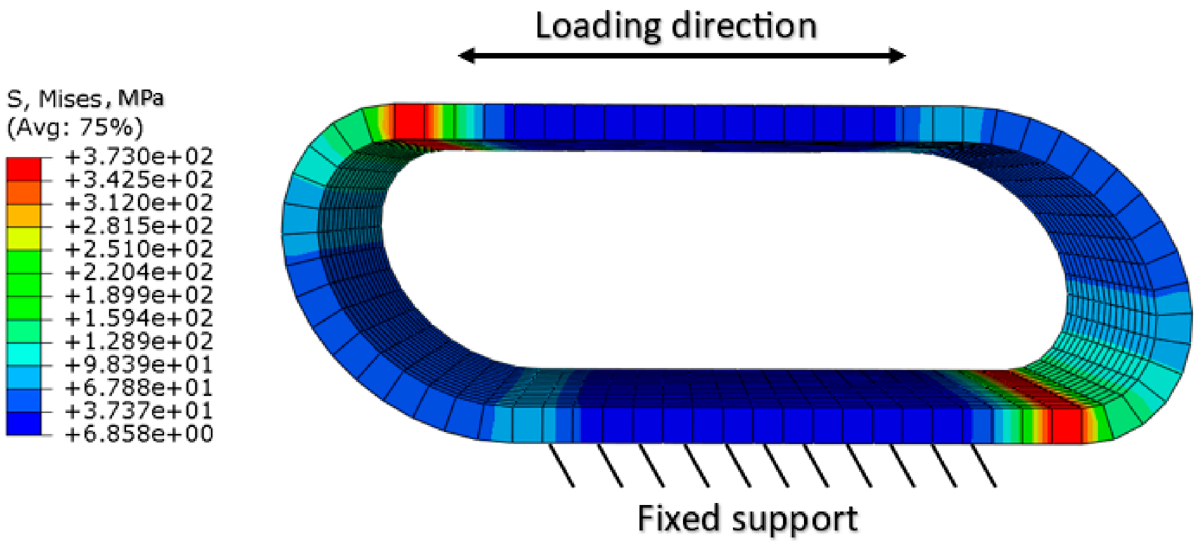

Figure 2. Developed stresses on a U-shaped damper.

3. Presumptions and Modeling

In the context of this study, two original steel moment-resisting frames were considered, one with 5 stories and another with 10 stories using SAP2000 v19. To retrofit these structures, a U-shaped metallic damper was added at each story employing an eccentrically bracing system. Each story featured three bays with a span of 5.5 m, and the height of each story was set at 3.5 m. Uniform dead loads of 200 kgf/m and live loads of 100 kgf/m were applied to each story. A rigid diaphragm assumption was made for all story levels to simplify the structural analysis. The steel material used for columns, beams, and braces was assumed to be A36, possessing a yielding strength of 250 MPa and an ultimate strength of 400 MPa. These modeling choices and assumptions were implemented to comprehensively evaluate the seismic performance of the steel moment-resisting frames retrofitted with U-shaped metallic dampers, allowing for a rigorous analysis of their effectiveness in enhancing structural resilience. Figure 3 illustrates the designs of the 5-story and 10-story frames, both with and without the damper. The structural member properties for the frames are detailed in Table 1.

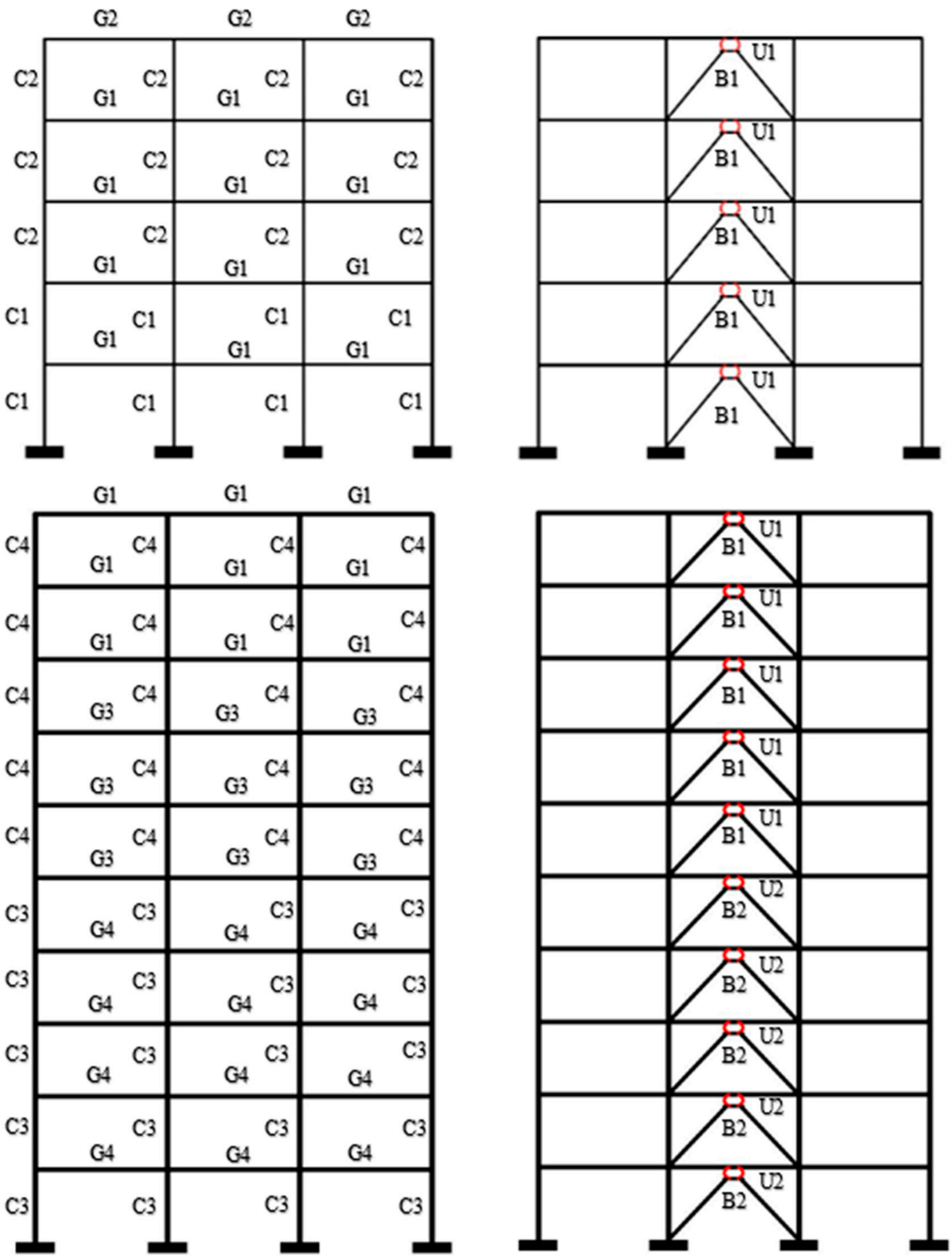

Figure 3. Schematic view of the studied original and retrofitted structures.

It should be noted that U1 dampers were used for 5-story structure and the second 5 stories of the 10-story structure. U2 dampers were also used for the first five stories of the 10-story structure.

In order to comprehensively evaluate the nonlinear behavior of structural components within the scope of this study, specific hinge properties were assigned to various structural elements. For beams, moment hinges were meticulously assigned at both ends of the members, whereas for columns, axial-moment hinges were diligently placed at both ends of these load-bearing elements. Additionally, for the braces, axial hinges were thoughtfully applied to capture their response characteristics. It is worth noting that all these assigned hinges were defined in strict accordance with the guidelines provided by ASCE 41, ensuring the adherence to industry standard practices for the modeling of structural components [27]. Furthermore, the connection between the dampers and the frame was established using a highly stiff element to ensure that the damper could serve as the primary defensive mechanism during earthquakes.

To seismically assess the behavior and performance of the structures using nonlinear time history analysis, a total of 10 ground motions were thoughtfully selected for this study. To maintain consistency and relevance in the selection process, the chosen ground motions adhered to specific criteria. These motions were carefully chosen to fall within a distance range of 15 to 50 km from the study site, ensuring that the seismic events closely represented a local seismic hazard. Furthermore, all selected ground motions exhibited a magnitude exceeding 6.5 on the Richter scale, providing a robust basis for evaluating the structures' response to substantial seismic events. Table 2 displays the selected ground motions listed in this study. To facilitate a rigorous analysis, each of these ground motions was meticulously scaled to align with the target design spectrum, ensuring that the seismic loading applied to the structures accurately reflected the expected seismic conditions. The scaled responses of the selected ground motions are shown in Figure 4.

Table 2. Selected ground motions.

Earthquake Name	Year	Station	Distance (km)	Magnitude (Mw)	PGA (g)	RSN
San Fernando	1971	Castaic-Old Ridge Route	19.33	6.61	0.32	57
Imperial Valley	1979	Cerro Prieto	15.19	6.53	0.17	164
Italy	1980	Brienza	22.54	6.9	0.22	288
New Zealand	1987	Matahina Dam	16.09	6.6	0.28	587
Loma Prieta	1989	Apeel 7-Pulgas	41.68	6.93	0.16	735
Cape Mendocino	1992	Shelter Cove Airport	26.51	7.01	0.23	830
Landers	1992	Morongo Valley Fire Station	17.36	7.28	0.22	881
Northridge	1994	Lake Hughes	20.77	6.69	0.17	1020
Hector	1999	Amboy	41.81	7.13	0.18	1762
Cape Mendocino	1992	Centerville Beach	16.44	7.01	0.32	3746

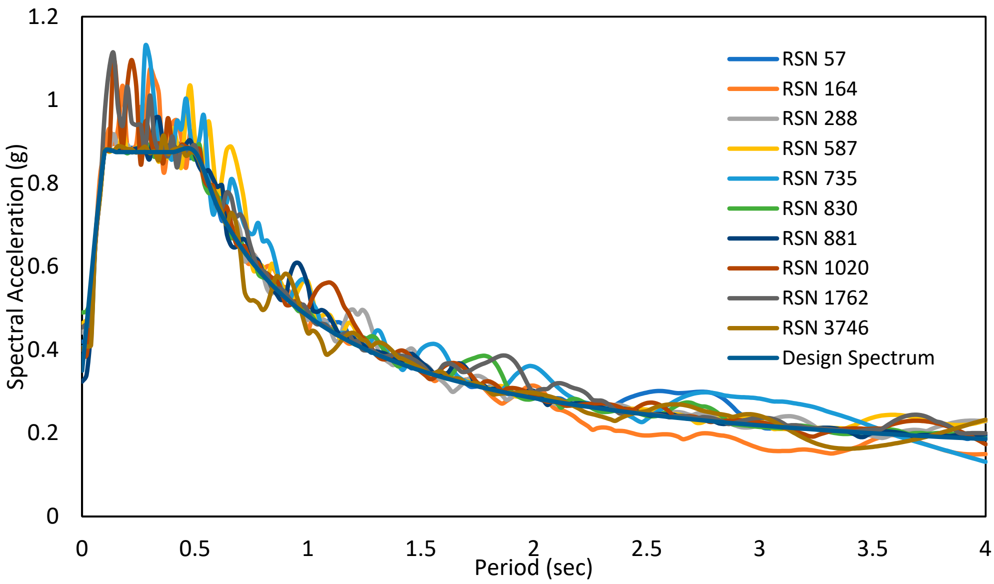

Figure 4. Response spectra of selected ground motions.

Endurance time analysis is an innovative and computationally efficient approach used in structural engineering to assess the seismic performance of structures, particularly when evaluating the effectiveness of supplemental damping devices such as U-shaped metallic dampers. Unlike traditional time history analysis, which requires simulating the dynamic response to multiple ground motion records, endurance time analysis focuses on capturing the cumulative damage experienced by a structure over an extended period during a seismic event.

In endurance time analysis, a representative ground motion record is selected, and the structural response is evaluated for a specified duration. The key concept is to assess the structure's ability to withstand seismic loading over time, considering factors such as energy dissipation, deformations, and the evolution of plastic hinges. This approach simplifies the analysis process compared to nonlinear time history analysis, making it computationally more efficient while still providing valuable insights into the structure's seismic performance.

Endurance time analysis has gained popularity, especially in the context of performance-based seismic design and the assessment of structural retrofitting strategies. It offers an effective means to evaluate the efficacy of supplemental damping systems and their impact on reducing structural damage and enhancing resilience. This method's efficiency makes it particularly useful for quick and reliable preliminary assessments of structural behavior under seismic loads.

In this study, publicly available artificial ETA functions were selected from the referenced website and used for the analysis [28,29]. Figures 5 and 6 show the acceleration time history and spectral acceleration of ETA20inx0, respectively. The selected ETA functions were then scaled to align with the accelerogram functions used in the time history analysis.

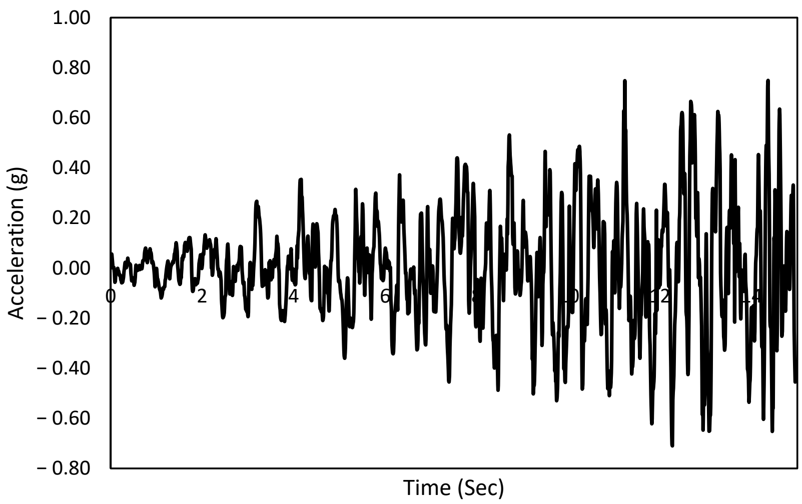

Figure 5. Acceleration time history of a single endurance time function.

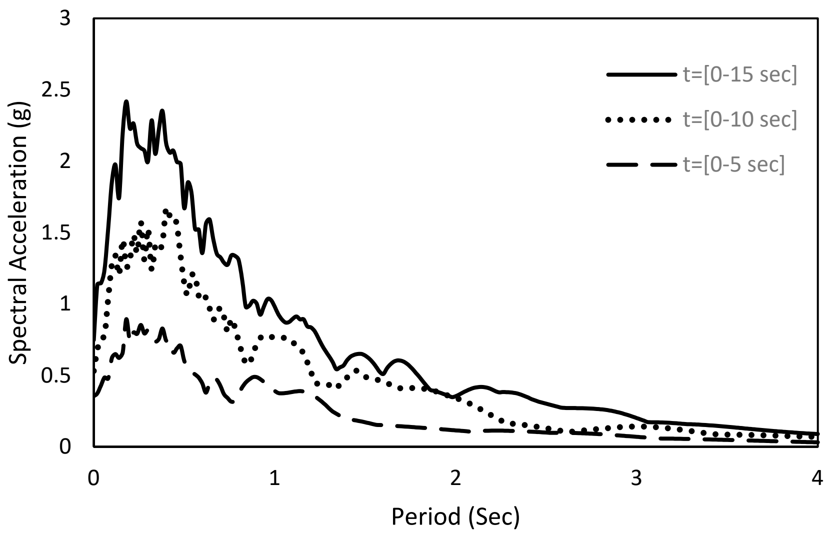

Figure 6. Spectral acceleration of the endurance time function at different time ranges.

4. Results and Discussion

In this section, the comprehensive results obtained from the study of two distinct steel moment-resisting frames are presented and analyzed. These structures, consisting of 5 and 10 stories, were originally modeled as the basis for seismic performance assessment. Furthermore, these base models were augmented by integrating metallic dampers, allowing for the evaluation of their profound influence on structural behavior when subjected to seismic loading.

The primary objective of this investigation was to shed light on the seismic resilience and effectiveness of metallic dampers as a retrofit strategy for existing steel structures, as well as a design consideration for new construction. The analysis encompasses a wide array of performance indicators, including inter-story drift, base shear forces, story accelerations, plastic hinge formation, and the hysteresis characteristics of the dampers.

Through this comprehensive study, critical questions within the realm of earthquake engineering are addressed, including the impact of the inclusion of metallic dampers on the overall seismic performance of steel moment-resisting frames in terms of structural integrity and safety, the extent to which inter-story drift is reduced by the dampers, the influence of metallic dampers on the distribution and magnitude of story shear forces, and the effect of dampers on story accelerations and their implications for occupant experience and structural health. Additionally, the study examined how metallic dampers mitigate the formation of plastic hinges and contribute to energy dissipation capacity while also delving into the hysteresis characteristics of the dampers and their role in energy dissipation and structural resilience. The ensuing discussions delve into the specifics of the findings and their implications for engineering practice, aiming to guide future endeavors in earthquake-resistant structural design and retrofitting strategies.

4.1. Eigenvalue Analysis

In this study, Eigenvalue analysis was employed to calculate the dynamic characteristics of the steel moment-resisting frames under investigation, with and without the incorporation of metallic dampers. The significance of this analysis lies in its capacity to determine the inherent oscillation frequencies and mode shapes of the structures, thereby providing crucial insights into their response to external forces, such as seismic excitation. It was observed that the natural frequencies of the structures were calculated, and a significant reduction in the natural period was achieved with the inclusion of metallic dampers. This reduction was primarily attributed to the increased lateral stiffness introduced by the dampers. This finding signifies an enhancement in the structures' ability to rapidly respond to seismic excitations, thereby potentially reducing structural damage. Furthermore, this comparative analysis between structures with and without dampers serves to validate the effectiveness of the damper systems, offering valuable insights for engineering design practices and contributing to the optimization of structural designs and retrofitting strategies aimed at enhancing seismic resilience in the built environment. The results of the Eigenvalue analysis are tabulated in Table 3.

Table 3. Eigenvalue analysis results.

	5 Story w/o damper	5 Story w/o damper	5 Story w/damper	5 Story w/damper	10 Story w/o damper	10 Story w/o damper	10 Story w/damper	10 Story w/damper
Mode	Natural Period (s)	Participation Factor (%)	Natural Period (s)	Participation Factor (%)	Natural Period (s)	Participation Factor (%)	Natural Period (s)	Participation Factor (%)
1	1.34	78	0.84	82	1.96	73	0.89	75
2	0.45	12	0.29	11	0.76	14	0.30	14
3	0.27	5	0.17	3	0.44	6	0.16	4

4.2. Inter-Story Drift

Inter-story drift, a critical parameter in the seismic performance evaluation of structures, holds paramount importance in ensuring both the safety of occupants and the integrity of buildings during seismic events. This parameter serves as a direct indicator of structural deformation and is instrumental in understanding the response of buildings to seismic forces. The significance of inter-story drift lies in its direct correlation with structural damage, occupant comfort, and overall structural performance during an earthquake. Excessive inter-story drift can lead to structural damage, impair the functionality of a building, and pose risks to the safety of occupants. Conversely, controlled and limited inter-story drift ensures not only the structural integrity of the building but also the preservation of functionality.

In the context of this study, which focuses on steel moment-resisting frames equipped with metallic dampers, the assessment of inter-story drift assumes particular importance. The integration of metallic dampers into these frames is intended to mitigate seismic-induced inter-story drift and its associated risks. Therefore, a detailed examination of inter-story drift, both with and without the presence of dampers, provides insights into the effectiveness of these dampers as a seismic retrofit strategy.

In the case of the 5-story structure, a substantial reduction in inter-story drift was achieved with the implementation of the damper. With the damper, the average inter-story drift was reduced by up to 50 percent. Similarly, for the 10-story structure, a significant reduction in inter-story drift was observed with the presence of the damper. With the damper, the average inter-story drift was reduced by up to 40 percent. Tables 4 and 5 list the inter-story drift results of the 5- and 10-story studied models, respectively.

Table 4. Inter-story drift results of the 5-story models.

Story No.	Drift Original Frame (%)		Drift Retrofitted Frame (%)		Reduction (%)	
	NTHA	ETA	NTHA	ETA	NTHA	ETA
1	0.0098	0.0098	0.0063	0.0057	35.7	41.8
2	0.0139	0.0127	0.0085	0.0078	38.8	38.5
3	0.0183	0.0170	0.0107	0.0102	41.5	40.0
4	0.0154	0.0148	0.0086	0.0080	44.1	45.9
5	0.0100	0.0106	0.0059	0.0061	41.0	42.4

Table 5. Inter-story drift results of the 10-story models.

Story No.	Drift Original Frame (%)		Drift Retrofitted Frame (%)		Reduction (%)	
	NTHA	ETA	NTHA	ETA	NTHA	ETA
1	0.0070	0.0069	0.0047	0.0041	32.8	40.5
2	0.0105	0.0102	0.0070	0.0059	33.3	42.1
3	0.0108	0.0094	0.0069	0.0075	36.1	20.2
4	0.0105	0.0103	0.0065	0.0059	38.1	42.7
5	0.0140	0.0148	0.0084	0.0067	40.0	54.7
6	0.0141	0.0151	0.0090	0.0086	42.5	43.0
7	0.0127	0.0135	0.0081	0.0082	36.2	39.2
8	0.0186	0.0183	0.0110	0.0100	40.8	45.3
9	0.0175	0.0165	0.0096	0.0092	45.1	44.2
10	0.0113	0.0111	0.0054	0.0050	52.2	54.9

To assess the reliability and effectiveness of the endurance time analysis method, a comparison was made with results obtained through the more detailed and computationally intensive nonlinear time history analysis. The objective was to evaluate whether a sufficiently accurate representation of structural behavior could be provided by the endurance time analysis, especially in the presence of dampers. The difference between the inter-story drift results obtained from the two methods was less than 5 percent, thus confirming the effectiveness and reliability of the endurance time analysis approach. It was concluded that endurance time analysis can serve as a valuable tool for the evaluation of the seismic performance of steel moment-resisting frames equipped with U-shaped metallic dampers, offering a computationally efficient alternative to the more resource-intensive nonlinear time history analysis. Inter-story drift results of the studied models are shown in Figure 7.

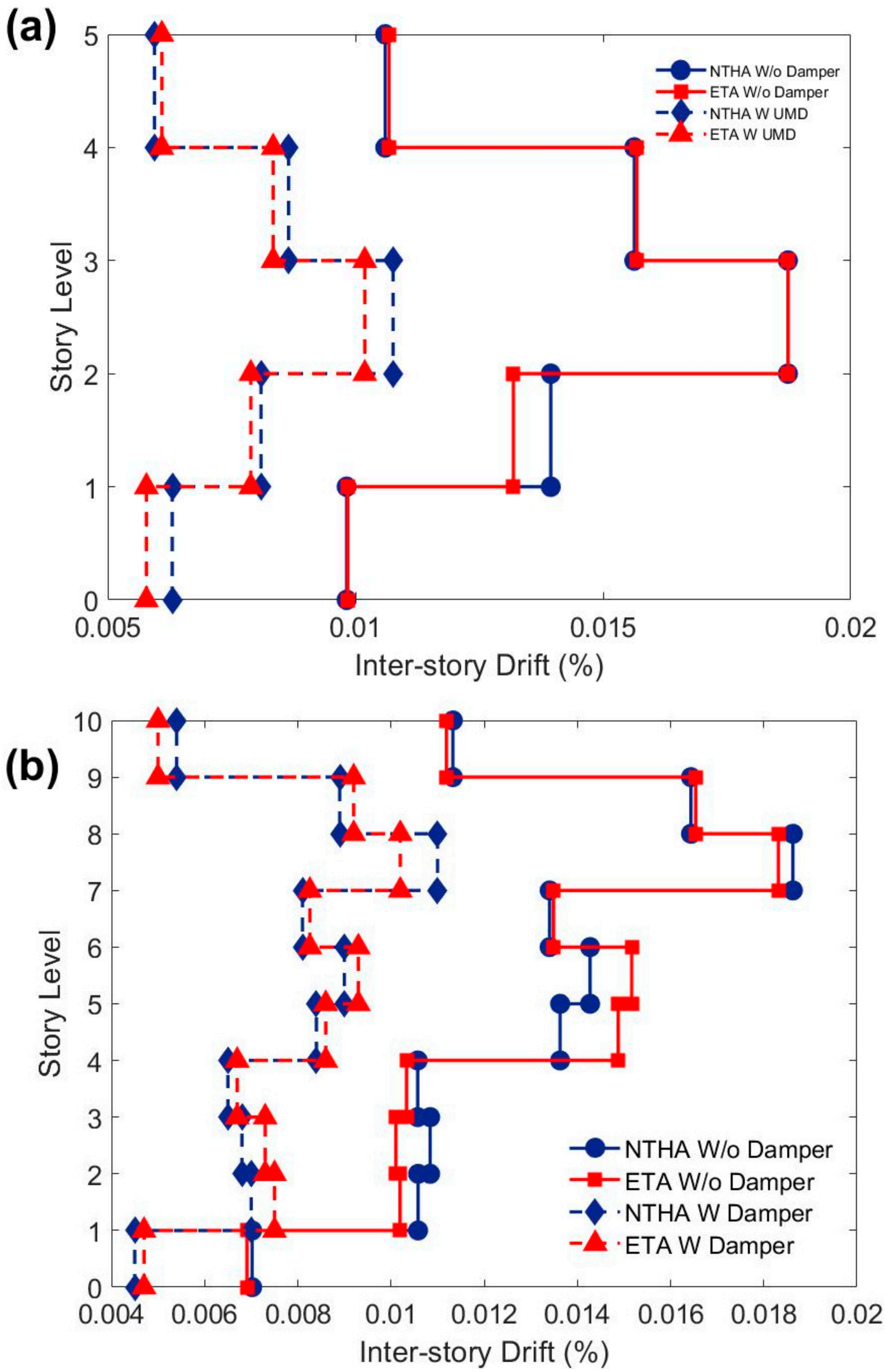

Figure 7. Inter-story drift results, (**a**) 5-story, (**b**) 10-story models.

4.3. Story Shear Force

The assessment of story shear force in the seismic performance evaluation of structures stands as a fundamental and pivotal aspect in understanding the response of buildings to lateral seismic loading. Story shear force represents the total lateral force that a structure must withstand during an earthquake, imparted primarily at its base.

The significance of story shear force analysis lies in its direct relevance to structural stability, safety, and design considerations. Understanding the magnitude and distribution of story shear force is essential for ensuring that a structure remains within its elastic range during seismic events, preventing structural failure or excessive deformation. Furthermore, story shear force is a key determinant in the design of lateral force-resisting systems, such as moment-resisting frames, which play a crucial role in safeguarding structures against seismic forces.

The introduction of the damper had a notable effect on reducing story shear forces in the 5-story structure. A comparison between the scenarios with and without dampers revealed that, in the absence of dampers, story shear forces were notably elevated. The average reduction achieved with the damper was up to 50 percent, signifying a significant reduction in story shear forces compared to the undamped condition. Similarly, for the 10-story structure, the damper demonstrated an effective reduction in story shear forces. Without dampers, story shear forces experienced considerable amplification. However, with the implementation of U-shaped metallic dampers, a substantial reduction of up to 40 percent in story shear forces was achieved, showcasing their efficacy in mitigating these forces. The results of the story shear forces are listed in Tables 6 and 7 for 5 and 10-story models, respectively.

Table 6. Story shear forces results for 5-story models.

Story No.	Shear Force Original Frame (N)		Shear Force Retrofitted Frame (N)		Reduction (%)	
	NTHA	ETA	NTHA	ETA	NTHA	ETA
1	655,217	661,176	504,495	451,214	23.0	31.7
2	594,592	566,730	453,148	425,358	23.8	24.9
3	518,408	528,593	396,110	374,326	23.6	29.2
4	436,676	439,428	332,744	305,994	23.8	30.3
5	290,804	289,249	217,350	204,129	25.2	29.4

Table 7. Story shear forces results for 10-story models.

Story No.	Shear Force Original Frame (N)		Shear Force Retrofitted Frame (N)		Reduction (%)	
	NTHA	ETA	NTHA	ETA	NTHA	ETA
1	1,015,904	982,468	784,075	823,944	22.8	16.1
2	969,145	916,754	738,636	792,141	27.8	13.6
3	915,524	830,388	709,728	734,744	22.5	11.5
4	838,917	827,731	670,137	673,079	20.1	18.7
5	776,753	811,008	616,965	609,671	20.5	24.8
6	715,066	743,873	549,675	557,840	23.1	25.0
7	638,138	653,427	474,714	480,614	25.6	26.4
8	545,903	555,916	414,417	419,343	24.1	24.5
9	452,283	460,711	325,221	321,504	28.1	30.2
10	276,120	270,326	184,588	176,858	33.1	24.5

The difference between the story shear force results obtained from the two methods was less than 5 percent, thus confirming the effectiveness and reliability of the endurance time analysis approach. This finding underscores the viability of endurance time analysis as a valuable tool for assessing the seismic performance of steel moment resisting frames equipped with U-shaped metallic dampers, providing a computationally efficient alternative to the resource-intensive nonlinear time history analysis. The comparative results of the story shear forces are shown in Figure 8.

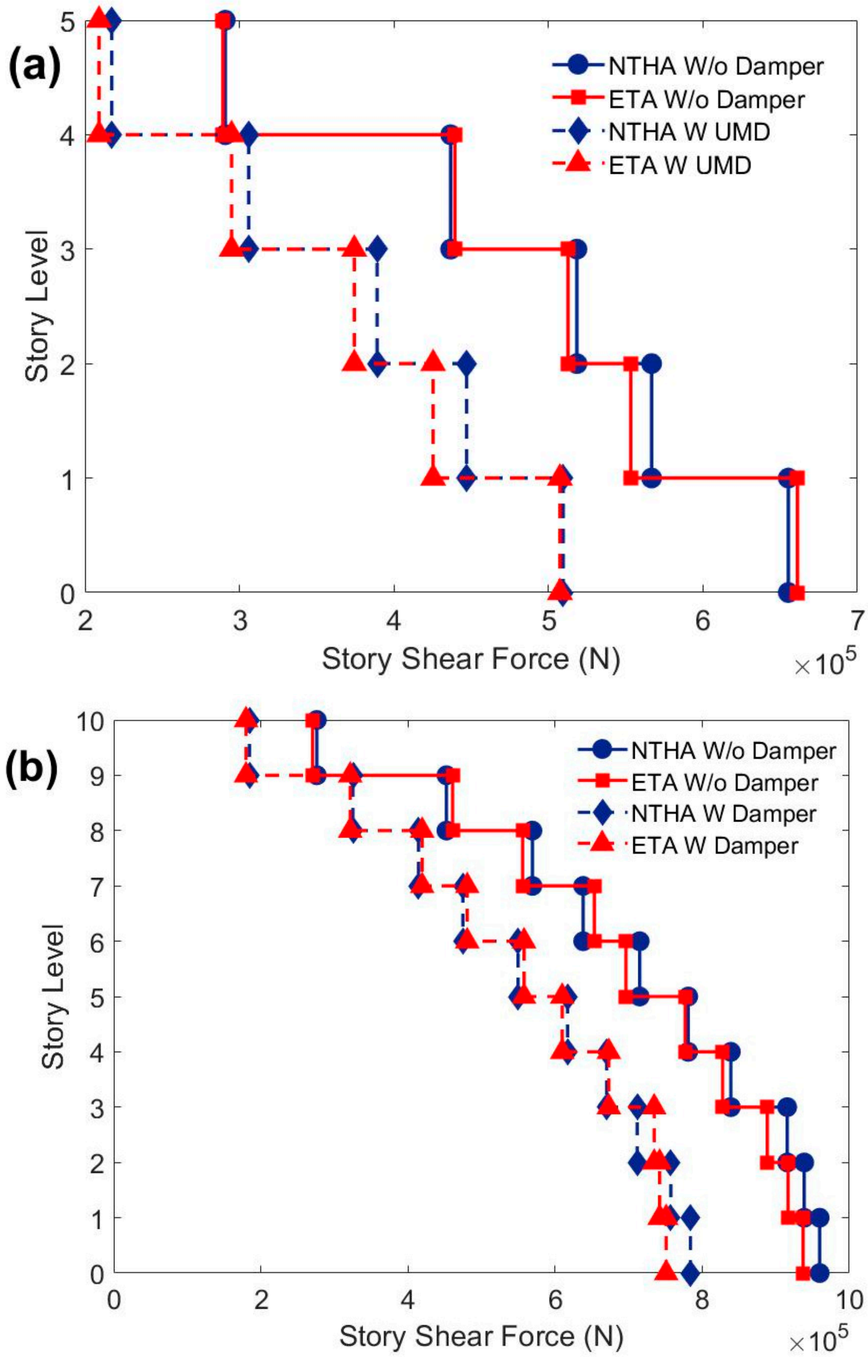

Figure 8. Story shear forces results, (**a**) 5-story, (**b**) 10-story models.

4.4. Incremental Dynamic Analysis

In addition to the nonlinear time history analysis, the incremental dynamic analysis was also extensively conducted on the original and retrofitted frames to evaluate the utilization of the U-shaped metallic dampers on the performance improvement of the steel structures. In this analysis, the seismic response of a structure is systematically examined by subjecting it to a series of ground motion records with increasing intensity levels. The key characteristic of IDA is the incremental nature of the loading, allowing for a step-by-step assessment of the structure's response to escalating seismic forces. Each incremental analysis provides valuable information regarding the structure's vulnerability, yielding a comprehensive understanding of its seismic performance under varying levels of ground motion intensity. By examining a structure's behavior across a range of seismic inputs, IDA facilitates the identification of critical failure modes and informs the development of effective seismic design and retrofitting strategies. This method has proven instrumental in enhancing the seismic resilience of structures and has become an integral component of seismic risk assessment in the field of structural engineering.

In this study, a set of ten seismic ground motions, as used in NTHA, was also utilized in IDA. In this work, the intensity measure was based on the peak ground acceleration of the selected seismic ground motions. The results of the intensity measure were plotted against the drift ratio. Therefore, the drift ratio was considered as the damage measure index. The results related to IDA were shown in Figure 9. According to the results, utilization of the U-shaped metallic damper noticeably improved the intensity measure. According to ASCE/SEI 41-17, the life safety performance level for the structural elements might be inferred to 2.0% drift ratio [27]. The IDA analyses illustrate that the required PGA for the retrofitted structures at that level of performance is significantly higher than that for the equivalent original frames. The results of the IDA analyses can be used as additional evidence of the efficiency of the U-shaped damper in retrofitting the steel structures. By utilizing this damper, the lateral displacement of the structures was reduced, resulting in a smaller drift ratio. In general, it is widely accepted that an excessive drift ratio may result in catastrophic damage to structures, and this parameter was successfully controlled in the retrofitted structures.

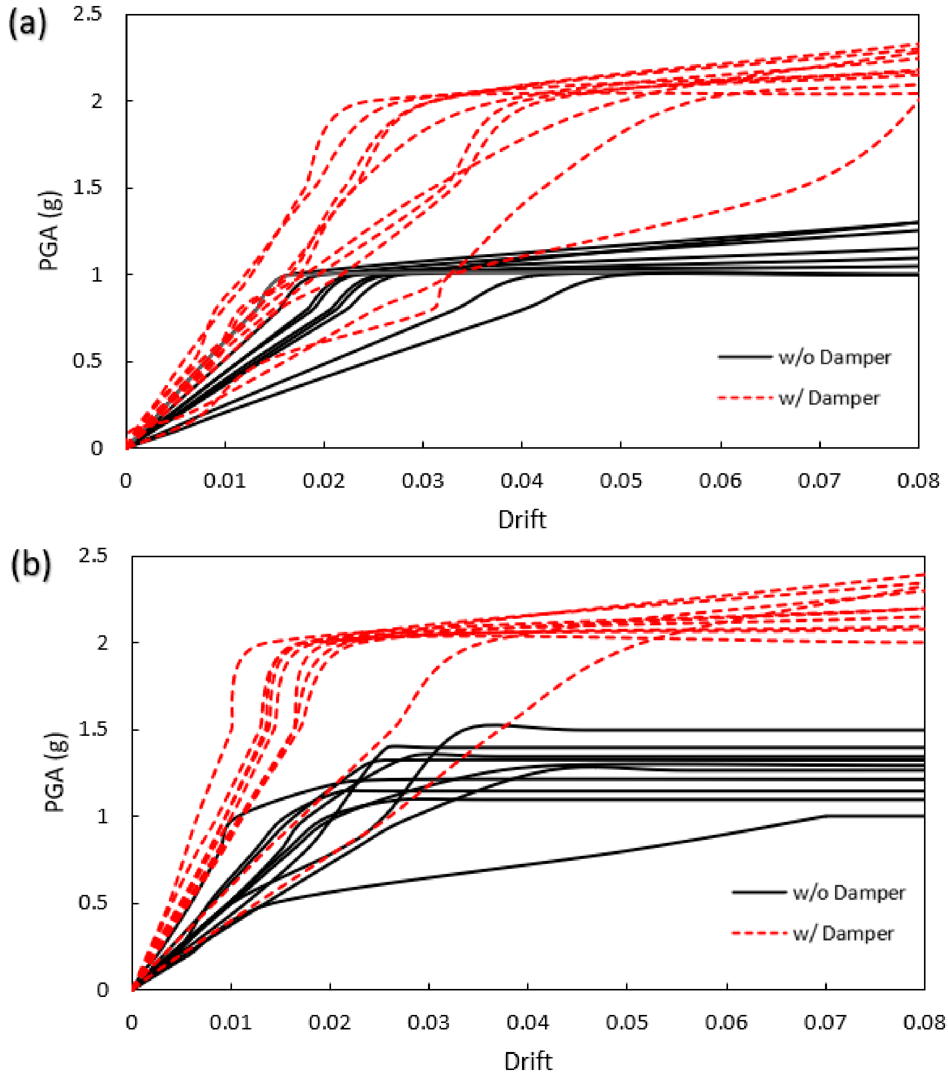

Figure 9. IDA curves for (**a**) 5-story, and (**b**) 10-story frames.

4.5. Plastic Hinge Formation

The formation of plastic hinges represents a critical juncture in the behavior of structural systems subjected to seismic forces. This phenomenon, while indicative of a structure's capacity to absorb energy and deform plastically without catastrophic failure, also signifies a loss of stiffness and the potential for reduced lateral load-carrying capacity. Therefore, understanding, controlling, and mitigating plastic hinge formation is of paramount importance in the seismic assessment and design of structures. The inclusion of metallic dampers within steel moment-resisting frames has emerged as a promising solution to enhance the seismic performance of these systems. This innovative approach not only reduces the overall demand on structural components but also influences the formation and behavior of plastic hinges. Consequently, a comparative analysis between the models equipped with metallic dampers and those without becomes imperative to assessing their respective performances in terms of plastic hinge formation. It was found that the inclusion of metallic dampers resulted in the lower formation of plastic hinges.

5. Conclusions

In this study, 5- and 10-story steel moment-resisting frames were considered. The original design of the structures was strengthened by adding U-shaped metallic dampers at each story level. A nonlinear finite elements analysis was conducted to evaluate the performance of U-shaped metallic dampers subjected to cyclic loading by considering large inelastic deformation. Nonlinear time history analysis along with incremental dynamic analysis were conducted on the structures both with and without the dampers to evaluate their performance. Since nonlinear time history analysis is time-consuming and computationally expensive, a new analysis called endurance time analysis (ETA) was also performed on the models. Comparative analyses were conducted for models both with and without the dampers, as well as for both methods of analysis. The main findings are as follows:

- ETA effectively assesses the performance of structures equipped with metallic dampers, and the results from this analysis closely match those from nonlinear time history analysis.
- Retrofitting structures with U-shaped metallic dampers can effectively reduce inter-story drift by up to approximately 55%.
- The inclusion of U-shaped metallic dampers can reduce story shear forces by up to approximately 33%.
- Results of the finite elements analysis showed that the U-shaped metallic damper can have a balanced hysteretic behavior which shows the efficiency of the damper for both tension and compression forces.
- According to IDA research, the corresponding original frames' PGA needed is substantially lower than that of the retrofitted structures at that level of performance.
- Fewer plastic hinges were formed in structures equipped with U-shaped metallic dampers, and these plastic hinges were associated with higher performance levels.

Author Contributions: Conceptualization, F.F.; methodology, F.F., F.E. and V.F.; software, F.F., F.E. and S.E.; validation, M.J.M. and V.F.; formal analysis, F.F., F.E. and S.E. and M.J.M.; investigation, F.F. and F.E.; resources, V.F.; data curation, F.F., F.E. and V.F.; writing—original draft preparation, F.F., F.E. and S.E.; writing—review and editing, F.F. and M.J.M.; supervision, V.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding authors.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Aghlara, R.; Tahir, M.M. A passive metallic damper with replaceable steel bar components for earthquake protection of structures. *Eng. Struct.* **2018**, *159*, 185–197. [CrossRef]
2. Saaed, T.E.; Nikolakopoulos, G.; Jonasson, J.-E.; Hedlund, H. A state-of-the-art review of structural control systems. *J. Vib. Control* **2015**, *21*, 919–937. [CrossRef]
3. Spencer, B.F.; Nagarajaiah, S. State of the Art of Structural Control. *J. Struct. Eng.* **2003**, *129*, 845–856. [CrossRef]
4. Titirla, M.D. A State-of-the-Art Review of Passive Energy Dissipation Systems in Steel Braces. *Buildings* **2023**, *13*, 851. [CrossRef]
5. Ghamari, A.; Kim, C.; Jeong, S. Development of an innovative metallic damper for concentrically braced frame systems based on experimental and analytical studies. *Struct. Des. Tall Spec. Build.* **2022**, *31*, e1927. [CrossRef]
6. Vargas, R.; Bruneau, M. Effect of Supplemental Viscous Damping on the Seismic Response of Structural Systems with Metallic Dampers. *J. Struct. Eng.* **2007**, *133*, 1434–1444. [CrossRef]
7. Javanmardi, A.; Ibrahim, Z.; Ghaedi, K.; Benisi Ghadim, H.; Hanif, M.U. State-of-the-Art Review of Metallic Dampers: Testing, Development and Implementation. *Arch. Comput. Methods Eng.* **2020**, *27*, 455–478. [CrossRef]
8. Benavent-Climent, A.; Escolano-Margarit, D.; Arcos-Espada, J.; Ponce-Parra, H. New Metallic Damper with Multiphase Behavior for Seismic Protection of Structures. *Metals* **2021**, *11*, 183. [CrossRef]
9. Avestaeifar, P.; Khezrzadeh, H. Experimental and numerical assessment of Piston Hybrid Frictional Metallic Damper (PHFMD). *Eng. Struct.* **2021**, *243*, 112669. [CrossRef]
10. Zhai, Z.; Guo, W.; Chen, W.; Yu, Z.; Zeng, C.; Li, S. Effect of damper failure on the seismic loss assessment of retrofitted steel moment-resisting frames. *Soil Dyn. Earthq. Eng.* **2021**, *150*, 106903. [CrossRef]
11. Kelly, J.M.; Skinner, R.I.; Heine, A.J. Mechanisms of energy absorption in special devices for use in earthquake resistant structures. *Bull. N. Z. Soc. Earthq. Eng.* **1972**, *5*, 63–88. [CrossRef]
12. Bergman, D.M.; Goel, S.C. *Evaluation of Cyclic Testing of Steel-Plate Devices for Added Damping and Stiffness*; Department of Civil Engineering, University of Michigan: Ann Arbor, MI, USA, 1987.
13. Cheng, S.; Du, S.; Yan, X.; Guo, Q.; Xin, Y. Experimental study and numerical simulation of clapboard lead damper. *Proc. Inst. Mech. Eng. C J. Mech. Eng. Sci.* **2017**, *231*, 1688–1698. [CrossRef]
14. Oh, S.-H.; Kim, Y.-J.; Ryu, H.-S. Seismic performance of steel structures with slit dampers. *Eng. Struct.* **2009**, *31*, 1997–2008. [CrossRef]
15. Takeda, Y.; Kimura, Y.; Yoshioka, K.; Furuya, N.; Takemoto, Y. An experimental study on braces encased in steel tube and mortal. In Proceedings of the Annual Meeting Architectural Institute of Japan, Tokyo, Japan, October 1976; pp. 1041–1042.
16. Tsai, K.-C.; Chen, H.-W.; Hong, C.-P.; Su, Y.-F. Design of Steel Triangular Plate Energy Absorbers for Seismic-Resistant Construction. *Earthq. Spectra* **1993**, *9*, 505–528. [CrossRef]
17. Farajiani, F.; Nekooei, M.; Mansoori, M.R. Study of vertical mass isolation structures equipped with metallic dampers with a focus on the position of stiff subsystem. *Structures* **2021**, *33*, 2824–2838. [CrossRef]
18. Wang, B.; Chen, P.; Zhu, S.; Dai, K. Seismic performance of buildings with novel self-centering base isolation system for earthquake resilience. *Earthq. Eng. Struct. Dyn.* **2023**, *52*, 1360–1380. [CrossRef]
19. Mohsenian, V.; Hajirasouliha, I.; Nikkhoo, A. Multi-level Response Modification Factor Estimation for Steel Moment-Resisting Frames Using Endurance-Time Method. *J. Earthq. Eng.* **2022**, *26*, 4812–4832. [CrossRef]
20. Hariri-Ardebili, M.A.; Sattar, S.; Estekanchi, H.E. Performance-based seismic assessment of steel frames using endurance time analysis. *Eng. Struct.* **2014**, *69*, 216–234. [CrossRef]
21. Estekanchi, H.E.; Vafaei, A.; Sadegh, A.M. Endurance time method for seismic analysis and design of structures. *Sci. Iran.* **2004**, *11*, 361–370.
22. Estekanchi, H.E.; Alembagheri, M. Seismic analysis of steel liquid storage tanks by Endurance Time method. *Thin-Walled Struct.* **2012**, *50*, 14–23. [CrossRef]
23. Riahi, H.T.; Estekanchi, H.E. Seismic assessment of steel frames with the endurance time method. *J. Constr. Steel Res.* **2010**, *66*, 780–792. [CrossRef]
24. Ebadi Jamkhaneh, M.; Ebrahimi, A.H.; Shokri Amiri, M. Experimental and Numerical Investigation of Steel Moment Resisting Frame with U-Shaped Metallic Yielding Damper. *Int. J. Steel Struct.* **2019**, *19*, 806–818. [CrossRef]
25. Nguyen, X.D.; Guizani, L. Analytical and numerical investigation of natural rubber bearings incorporating U-shaped dampers behaviour for seismic isolation. *Eng. Struct.* **2021**, *243*, 112647. [CrossRef]
26. Dolce, M.; Filardi, B.; Marnetto, R.; Nigro, D. Experimental tests and applications of a new biaxial elasto-plastic device for the passive control of structures. *Spec. Publ.* **1996**, *164*, 651–674.
27. *ASCE 41-17*; Seismic Evaluation and Retrofit of Existing Buildings. American Society of Civil Engineers: Reston, VA, USA, 2017.

28. Estekanchi, H.E. Endurance Time Method Website. 2022. Available online: www.sites.google.com/site/etmethod (accessed on 16 January 2022).
29. Ahmadie Amiri, H.; Hosseini, M.; Estekanchi, H.E. Efficient seismic risk assessment of irregular steel-framed buildings through endurance time analysis of consistent fish-bone model. *Struct. Des. Tall Spec. Build.* **2022**, *31*, e1901. [CrossRef]