ORIGINAL RESEARCH

Evaluation of Yielding Dampers in Diagonal Bracing Systems Based on the Perforation Arrangement in the Damper Plate

Jafarpour S.[1,*]

Abstract:

This research investigates the impact of various slit configurations in diagonal braces of concentrically braced frames using nonlinear finite element analysis in Abaqus software. The primary objective of this study is to optimize the seismic performance of these systems by utilizing yielding dampers and modifying the geometry of slits in damper plates. Several structural models were subjected to cyclic loading, and key parameters such as ultimate strength, energy absorption, stress distribution, plastic strain, and hysteretic behavior were comprehensively analyzed. The results indicate that when the slits are uniformly distributed across the surface of the damper, the system effectively utilizes the plastic capacity of the plate and achieves higher energy dissipation. Changes in the shape and pattern of slits significantly affect the distribution of plastic strain, stress concentration, and the reduction of strength in the final cycles. Therefore, optimizing slit designs can effectively enhance the seismic performance of structures. This study provides recommendations for improving brace designs, making a significant contribution to the safety and efficiency of earthquake-resistant structures.

Keywords:
Yielding damper, concentrically braced frame, nonlinear analysis, energy absorption, stress distribution, seismic performance, Abaqus software, slits, hysteresis.

*Corresponding author Email: samanehjafarpour10@gmail.com
1 Department of Civil Engineering, South Tehran Branch, Islamic Azad University, Tehran, Iran

1. Introduction

Earthquake-resistant design has become a cornerstone of modern structural engineering, particularly in regions prone to seismic activity. Among the various strategies developed to mitigate seismic forces, yielding dampers have emerged as a highly effective solution [1].These devices are designed to absorb and dissipate seismic energy, thereby reducing the forces transmitted to primary structural elements[2]. Yielding dampers, such as steel slit dampers (SSDs), are often integrated into concentrically braced frames (CBFs) or eccentrically braced frames (EBFs) to enhance ductility and energy dissipation [3].Despite their proven effectiveness, there remains a significant gap in understanding how specific geometric and dimensional variations in damper designs influence their overall performance under seismic loading conditions [4]. Concentrically braced frames equipped with yielding dampers have gained widespread adoption due to their ability to provide both stiffness and energy absorption[5]. However, these systems face challenges during intense seismic events, particularly near-fault earthquakes, where high stress concentrations at brace-to-beam and brace-to-column connections can lead to failure[6]. To address this issue, researchers have explored various methods, including the use of buckling-restrained braces, shear walls, and innovative yielding dampers[7]. Yielding dampers, in particular, have shown promise as they dissipate seismic energy through plastic deformation, thereby protecting the main structural components from damage[8]. Nevertheless, optimizing the geometry and dimensions of these dampers remains a critical area of investigation .In recent years, several studies have contributed valuable insights into the behavior of yielding dampers under cyclic loading. For instance, in 2020, Chen et al. introduced a behavioral model to study the pinching phenomenon in yielding shear panel dampers (YSPD)[9]. Their findings demonstrated that YSPDs could dissipate up to 70% of seismic energy, with the pinching effect accounting for only 10% of the hysteretic response [10]. This research highlighted the importance of understanding energy dissipation mechanisms in dampers and laid the groundwork for further investigations. Similarly, Ito and colleagues (2011) proposed a novel damper composed of perforated steel plates combined with buckling-resistant wooden panels[11]. Through hybrid nonlinear tests on a three-story building equipped with stud dampers, they observed that the dampers exhibited high ductility and stability under large displacements, effectively reducing out-of-plane deformations in the steel plates[12].Building on these advancements, Kafi et al. (2019) conducted parametric studies on the geometric configurations of slit dampers[13]. By examining eight small-scale slit dampers installed on column surfaces, they identified optimal settings for these devices. Their research demonstrated that slit dampers exhibit good resistance to both shear and bending forces[14]. To achieve optimal design, they considered two distinct yielding mechanisms shear yielding and flexural yielding and compared the strength and ductility of the connections[15]. This work emphasized the importance of tailoring damper geometry to maximize performance.

Further innovations were introduced by Cheraghi et al. (2017), who investigated a new type of multi-phase damper consisting of nested tubes capable of altering dynamic parameters such as resistance, stiffness, and damping ratio [16]. Through quasi-static cyclic tests, they evaluated the damper's energy absorption capacity, ductility, and hysteresis behavior Notably, their dampers achieved viscous damping ratios of up to 38%, demonstrating their effectiveness in mitigating seismic forces This study exemplified the potential of adaptive damper designs to address diverse seismic demands.

Maheri et al. (2019) introduced a pure torsional yielding damper, which generated uniform stress distribution across the entire thickness of its tubular walls Experimental tests on ten specimens confirmed the damper's stable and well-formed hysteresis loops, along with its high energy dissipation capacity. The researchers also derived analytical relationships to predict the structural characteristics of the damper, achieving excellent agreement between experimental and theoretical results. This work highlighted the value of combining experimental validation with analytical modeling to refine damper designs [17].

Despite these advancements, there remains a lack of comprehensive understanding regarding how specific geometric parameters, such as slit width, length, and spacing, influence the overall behavior of yielding dampers This study aims to address this gap by investigating the impact of slit configurations on the seismic response of CBFs using nonlinear finite element analysis in ABAQUS. Parameters such as ultimate strength, energy absorption, plastic strain distribution, stress concentration, and hysteresis behavior will be comprehensively examined [18].
By synthesizing previous research and leveraging advanced numerical tools, this study seeks to advance the state of knowledge in seismic engineering and pave the way for future innovations in damper technology. The results will not only enhance the efficiency and safety of structures equipped with yielding dampers but also contribute to reducing human and economic losses caused by earthquakes[19]. Ultimately, this research aims to propose a new generation of yielding dampers with superior performance, offering a practical solution for improving the seismic resilience of buildings worldwide.

2. Description of the Proposed Method

The proposed method in this research focuses on investigating the impact of various slit configurations in yielding dampers on the seismic performance of concentrically braced frames (CBFs). The study employs nonlinear finite element analysis using ABAQUS software to simulate and evaluate the behavior of these systems under cyclic loading. This section provides a detailed description of the methodology, including the design concept, geometric parameters, material properties, numerical modeling, and loading protocols

2.1. Validation

To ensure the accuracy and reliability of the numerical models developed in this study, a comprehensive validation process was conducted by comparing the results obtained from the finite element analysis in ABAQUS with experimental data reported in prior research. Specifically, the hysteresis loops derived from the numerical simulations were compared with those obtained from laboratory tests on similar yielding dampers, as detailed in the study by Chen and Albermani [1].The comparison revealed excellent agreement between the two sets of results, demonstrating the validity of the modeling approach. As shown in Figure 1, the hysteresis curves exhibit stable and well-defined loops, indicating consistent energy dissipation behavior under cyclic loading. Both the numerical and experimental models displayed symmetrical hysteresis loops with minor discrepancies in terms of maximum load-bearing capacity and residual deformation, which can be attributed to material variability and boundary condition assumptions in the numerical model. Furthermore, the backbone curves, which represent the envelope of the hysteresis loops, also showed strong alignment between the experimental and simulated results. This level of consistency confirms that the finite element model accurately captures the nonlinear behavior of the yielding damper, including its plastic deformation and energy absorption characteristics. The successful validation not only enhances confidence in the numerical methodology but also provides a robust framework for further parametric studies aimed at optimizing the design of yielding dampers for improved seismic performance.

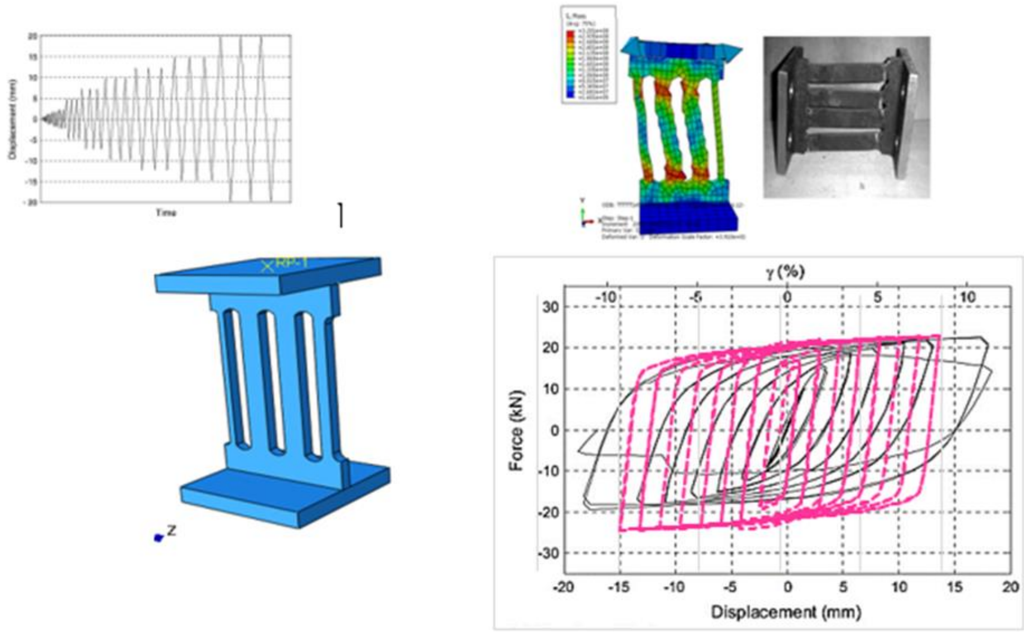


Figure 1: Figure 1 Comparison of Hysteresis Curves for the Validation of the Yielding Damper

Design Concept and Geometry

The research investigates a novel yielding damper integrated into diagonal braces of concentrically braced frames. The frame configuration is adapted from Gray and colleagues' study [20] featuring a single-bay frame with a span of 4.2 meters and a height of 3.2 meters. The diagonal brace is equipped with a yielding damper designed to absorb and dissipate seismic energy through plastic deformation.

The yielding damper consists of perforated steel plates with a thickness of 4 mm and a 50% perforation ratio. The arrangement of slits is considered the primary variable in this study, as it significantly influences the damper's hysteretic behavior, energy absorption capacity, and stress distribution. The beam is modeled using an IPE 300 profile, while the columns are constructed from HEA 220 profiles. The diagonal brace connected to the damper is made from IPE 180. Figure 2 illustrates the frame configuration and the placement of the yielding damper.

2.2. Material Properties and Nonlinear Behavior

The materials used in the study are modeled based on S235JR steel, as detailed in Tables 1&2 of the research. The elastic properties include a Young's modulus of 2.1×10
11
N/m², a Poisson's ratio of 0.3, and a mass density of 7850 kg/m³. The plastic properties are defined by yield stresses at various strain levels, ensuring accurate representation of the material's nonlinear behavior under cyclic loading.

The nonlinear behavior of the steel is modeled using a bilinear stress-strain relationship, accounting for strain hardening effects. This approach ensures that the simulation captures the ductility and energy dissipation capabilities of the yielding damper accurately.

2.3. Finite Element Modeling

The finite element model was developed in ABAQUS, a robust tool for simulating complex structural behaviors. The modeling process involved several key steps:

Geometry Creation : The frame geometry, including beams, columns, braces, and the yielding damper, was created using the Part module in ABAQUS. The dimensions and profiles of the structural elements were carefully defined to match the experimental setup described by Gray et al [20]. .Meshing Strategy : To ensure accurate results, the meshing strategy was tailored to the specific requirements of the study. Shell elements (S4R) were used for the frame components (beams and columns), while solid elements (C3D8R) were employed for the yielding damper and its connecting arms. The interaction between the damper and the brace was explicitly modeled using contact definitions in ABAQUS, ensuring realistic simulation of the system's behavior.

Boundary Conditions and Loading : The frame was subjected to cyclic displacement-controlled loading according to the ATC-24 protocol, which involves progressively increasing displacement amplitudes to induce plastic deformation. Boundary conditions were defined to replicate the experimental setup, with fixed supports at the base of the columns.

Material Calibration : The material properties were calibrated based on experimental data from prior studies to ensure realistic simulation outcomes. Parameters such as yield strength, ultimate strength, and strain-hardening characteristics were input into the model to replicate the mechanical behavior of the steel plate.

To evaluate the effects of various slit configurations in yielding dampers, five distinct models were designed and examined. Each model was named based on its geometric characteristics and slit pattern, which is considered the main variable in this study. The models include TP-A (yielding damper with annular perforations), TP-B (yielding damper with square perforations arranged in a lattice), TP-C (yielding damper with vertical hourglass-shaped slits), TP-D (yielding damper with elliptical vertical slits spaced closely), and TP-E (yielding damper with symmetric divergent angled slits). This classification aims to facilitate the comparison of model performance and provide structured results. A schematic and description of each model are presented in Figure 3. This figure clearly shows how each model was designed and highlights the differences between them.

Table 1Mechanical and Physical Properties of S235 JR Steel for Abaqus Simulation

Property	Value	Unit
Young’s Modulus (E)	210	Mpa
Poisson’s Ratio (ν)	0.3	–
Density (ρ)	7850	kg/m³
Yield Strength (σ_y)	235	MPa
Ultimate Tensile Strength (σ_u)	360	MPa

Table 2Plastic Stress-Strain Data

Plastic Strain	Yield Stress
0	235
0.02	300
0.05	340
0.1	380
0.15	410
0.2	430

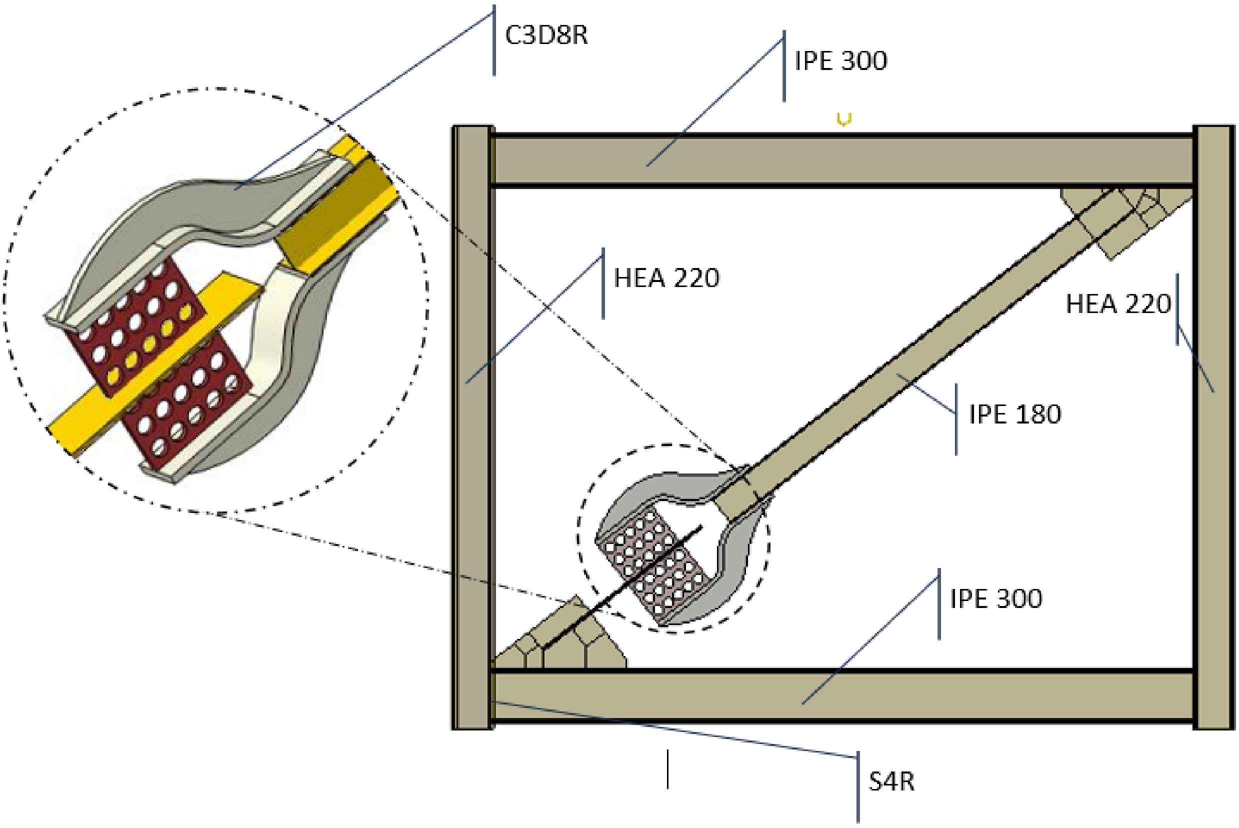


Figure 1. Details of Sections Along with Element Types in the Proposed Damper

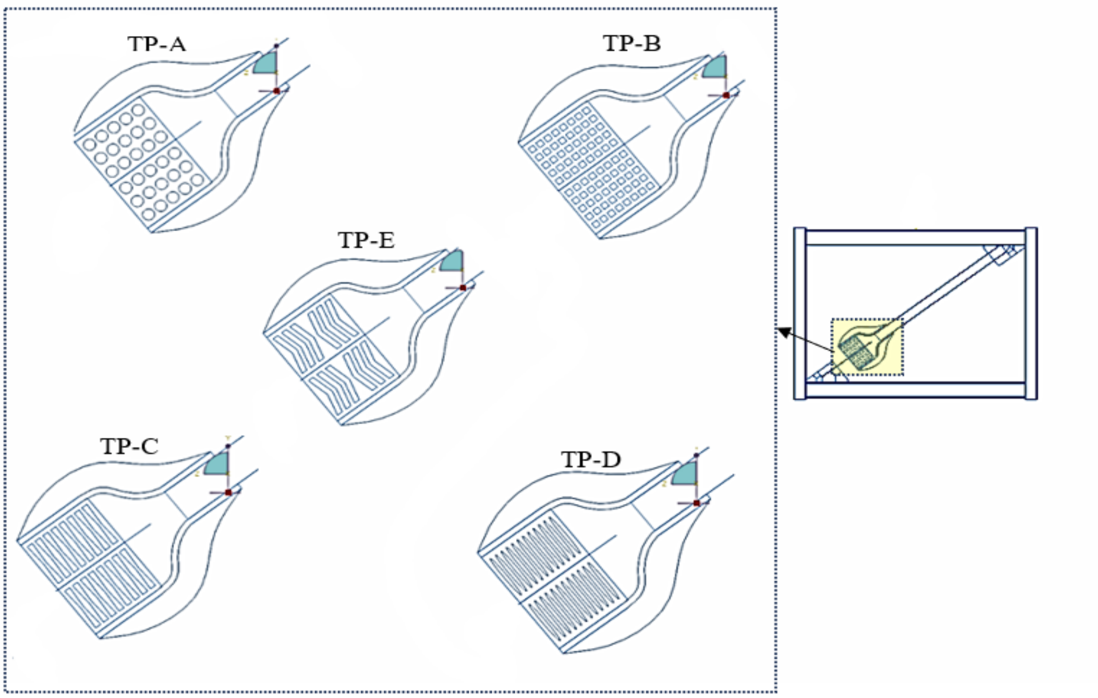


Figure 2. Model Naming Based on the Variability of the Yielding Damper Plate

2.4. Von Mises Stress Distribution and Damage Potential Based on the PEEQ Criterion

In this section, the distribution of von Mises stress and plastic strain, as well as the potential for damage across different damper models, is analyzed. Based on the simulation results obtained from ABAQUS, it was observed that the design of the slits significantly influences the stress and damage distribution patterns within the damper plates. As shown in Figure 4 , which illustrates the von Mises stress and equivalent plastic strain contours, models TP-A and TP-C exhibit a notably more uniform distribution of stress and damage throughout the damper plate compared to other configurations.This uniform distribution enhances the energy dissipation capacity of the system by preventing localized yielding and delaying premature failure. Furthermore, the absence of concentrated stress zones contributes to improved fatigue resistance and overall structural integrity. Consequently, these models demonstrate not only superior seismic performance but also greater durability under cyclic loading conditions typically associated with earthquake excitations.

On the other hand, models such as TP-C, which incorporate hourglass-shaped slits, exhibited significantly higher stress concentrations at the corners and extremities of the slits. These localized stress peaks accelerate damage accumulation in those regions, ultimately diminishing the damper's ability to absorb energy during seismic events. Furthermore, although the overall stress distribution patterns within the structural frames remained relatively consistent across all models, the dampers displayed notable variations depending on slit configuration — with certain designs showing pronounced stress localization that highlights inherent weaknesses in their geometry.For instance, in model TP-A, the stress distribution was comparatively lower at critical beam-column connection zones, allowing the damper to yield earlier and more uniformly, thereby reducing the risk of premature failure. This observation suggests that an optimized slit design can effectively mitigate stress concentrations in vulnerable areas, leading to improved structural integrity and an extended service life under cyclic loading conditions. Hence, the geometric configuration of slits plays a crucial role in enhancing the overall seismic resilience of the structure.

2.5. Analysis of Results: Hysteresis Loops and Buckling Behavior

The evaluation of hysteresis loops and buckling behavior provided key insights into the seismic performance of the various slit configurations, as further illustrated in Figure 5. A stable and full hysteresis loop indicates superior energy dissipation capacity and structural stability under repeated loading cycles, both of which are essential for effective seismic response. All models demonstrated some degree of stable hysteresis behavior, reflecting their general suitability for energy absorption; however, significant differences were observed in loop size and symmetry, directly linking slit geometry to overall damping efficiency.For example, models TP-B (featuring square lattice perforations) and TP-D (with vertical elliptical slits) produced symmetric and wide hysteresis loops, indicating excellent energy dissipation and consistent cyclic behavior. In contrast, model TP-E, which employed divergent angled slits, exhibited narrower and less stable loops, suggesting a reduced capacity to absorb seismic energy and maintain structural stability over multiple loading cycles. These findings clearly demonstrate that the shape and orientation of slits have a direct and measurable impact on the hysteretic performance of the system.Moreover, the buckling behavior varied considerably among the models, with those featuring more regular and uniform slit patterns exhibiting higher resistance to global buckling and delayed onset of structural failure. This implies that carefully designed slit configurations not only improve energy dissipation but also enhance structural robustness by increasing the load-carrying capacity before instability occurs.

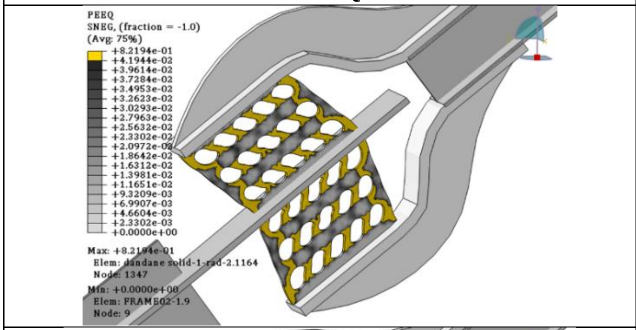
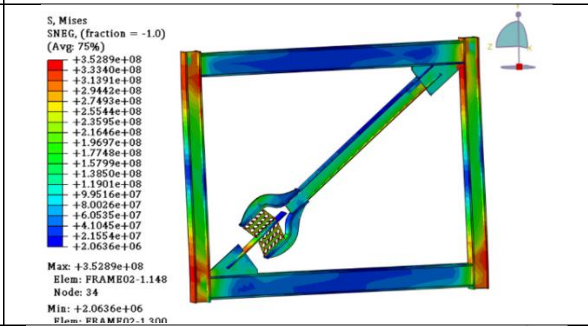
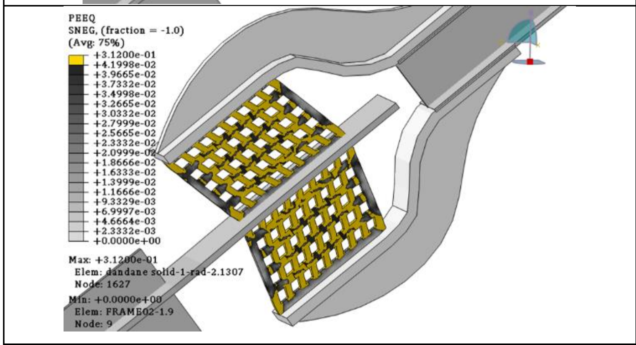
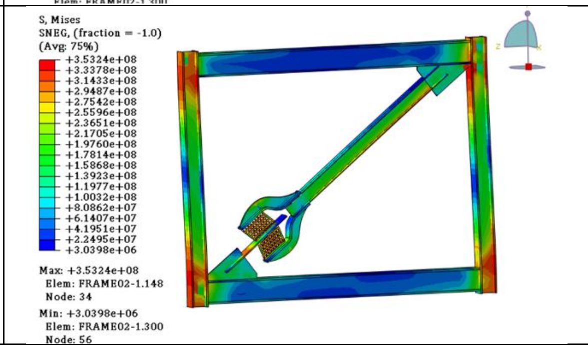
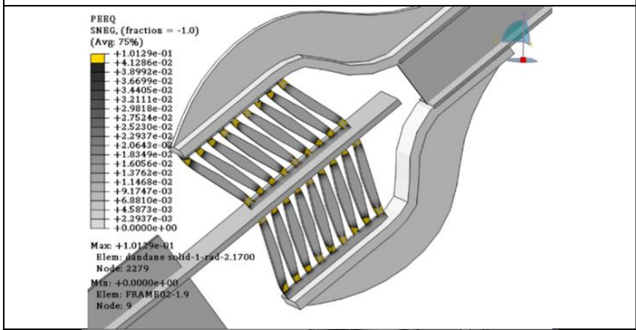
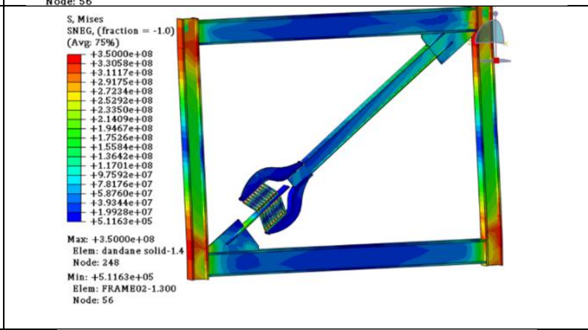
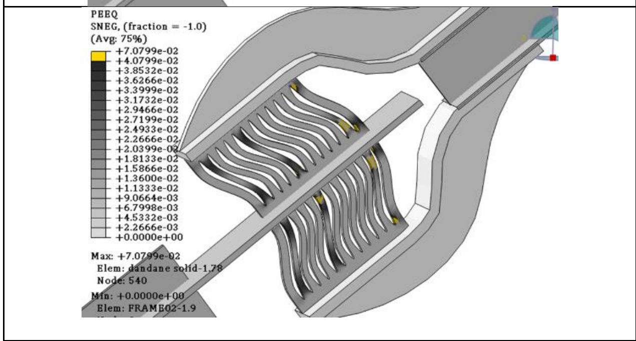
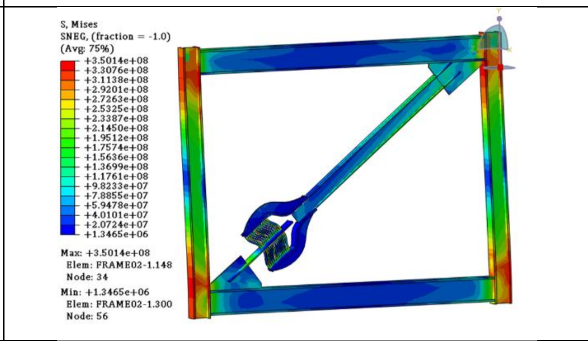
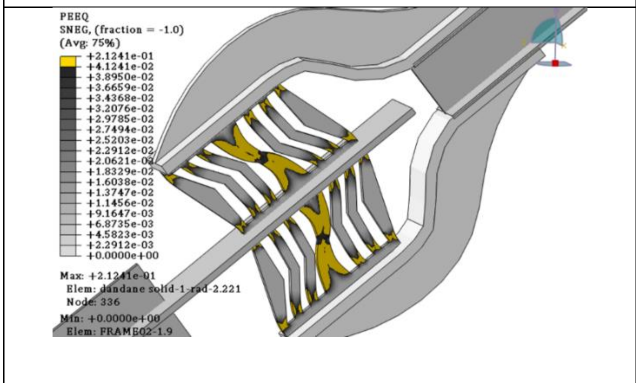
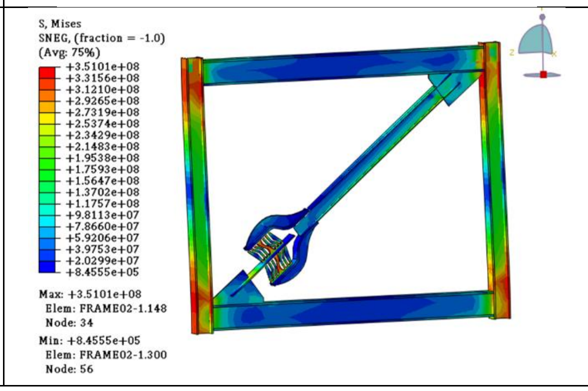
PEEQ	Von Mises Stress Distribution	
		TP-A
		TP-B
		TP-C
		TP-D
		TP-E

Figure 3. Results Related to Stress and Plastic Strain Distribution in the Yielding Damper Plates

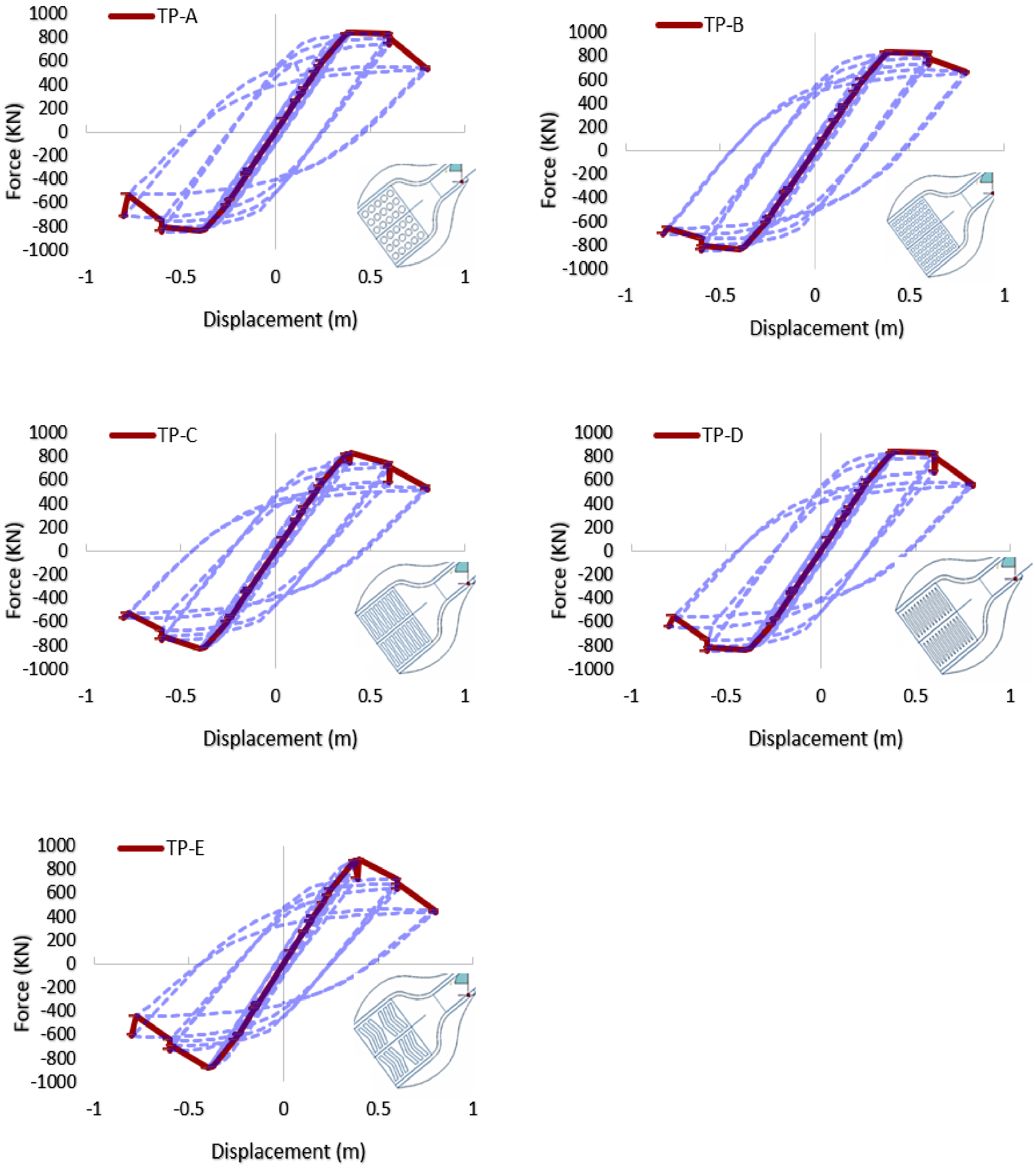


Figure 4. Results of Hysteresis Loops and Backbone Curves

The analysis of hysteresis curves in this study reveals that the design of slits and the distribution of stress in yielding dampers play a crucial role in the seismic performance of structures. One significant finding is that none of the hysteresis loops exhibited pinching behavior. This absence of pinching can be attributed to the uniform distribution of stress and the prevention of localized stress concentrations, which enhances the plastic deformation capacity of the dampers. In models where localized stresses were minimized and damage was distributed more evenly, the end loops of the hysteresis curves were thicker and more stable. This indicates that an optimal slit design can reduce localized damage and increase energy absorption capacity.Overall, the area under the backbone curve in the studied cases did not exceed 12%, highlighting the limited energy dissipation capacity of the systems. This limitation may be related to factors such as slit geometry and the distribution of plastic strain. Additionally, it was observed that the backbone curve area was larger in models with divergent slits compared to other models. This suggests that divergent slits can provide higher energy absorption capacity but still require further optimization to mitigate strength degradation during later cycles.In conclusion, this research demonstrates that appropriate slit design can significantly enhance the seismic performance of structures. For instance, models with regular and symmetric slits showed better performance in terms of energy absorption and bility of the hysteresis loops. These findings can serve as a foundation for developing more optimized designs in future studies.

3. Conclusions

This research investigates the impact of slit geometry and dimensions in yielding dampers to enhance the seismic performance of concentrically braced frames. Using numerical simulations in ABAQUS, various designs were evaluated, and key parameters such as ultimate strength, energy absorption, stress distribution, plastic strain, and hysteretic behavior were comprehensively analyzed. The results demonstrate that variations in slit shape and arrangement significantly affect structural performance. Regular and symmetric designs led to more uniform plastic strain distribution and reduced stress concentrations in critical areas, while irregular or asymmetric designs exhibited weaker performance.

Additionally, the analysis of hysteresis loops revealed that optimized designs can provide higher energy absorption capacity and prevent strength degradation during later loading cycles. These findings highlight that focusing on optimizing slit geometry and dimensions can effectively improve the seismic performance of structures. Ultimately, this study provides recommendations for future designs that can serve as a foundation for developing innovative methods in the field of structural bracing systems.

Reference

[1] R. W. Chan and F. Albermani, "Experimental study of steel slit damper for passive energy dissipation," *Engineering structures,* vol. 30, no. 4, pp. 1058-1066, 2008.

[2] M. D. Titirla, P. K. Papadopoulos, and I. N. Doudoumis, "Finite element modelling of an innovative passive energy dissipation device for seismic hazard mitigation," *Engineering Structures,* vol. 168, pp. 218-228, 2018.

[3] M. Paronesso and D. G. Lignos, "Seismic design and performance of steel concentrically braced frame buildings with dissipative floor connectors," *Earthquake Engineering & Structural Dynamics,* vol. 51, no. 15, pp. 3505-3525, 2022.

[4] I. Takewaki and H. Akehashi, "Comprehensive review of optimal and smart design of nonlinear building structures with and without passive dampers subjected to earthquake loading," *Frontiers in Built Environment,* vol. 7, p. 631114, 2021.

[5] Y. Bakhshayesh, M. Shayanfar, and A. Ghamari, "Improving the performance

of concentrically braced frame utilizing an innovative shear damper," *Journal of Constructional Steel Research*, vol. 182, p. 106672, 2021.

[6] J. Shen, O. Seker, B. Akbas, P. Seker, S. Momenzadeh, and M. Faytarouni, "Seismic performance of concentrically braced frames with and without brace buckling," *Engineering Structures*, vol. 141, pp. 461-481, 2017.

[7] S. Hu, C. Qiu, and S. Zhu, "Machine learning-driven performance-based seismic design of hybrid self-centering braced frames with SMA braces and viscous dampers," *Smart Materials and Structures*, vol. 31, no. 10, p. 105024, 2022.

[8] R. Zhang, C. Wang, C. Pan, H. Shen, Q. Ge, and L. Zhang, "Simplified design of elastoplastic structures with metallic yielding dampers based on the concept of uniform damping ratio," *Engineering Structures*, vol. 176, pp. 734-745, 2018.

[9] R. W. Chan, F. Albermani, and M. S. Williams, "Yielding shear panel device for passive energy dissipation," in *Progress in Mechanics of Structures and Materials*: CRC Press, 2020, pp. 843-848.

[10] M. M. Javidan, S. Chun, and J. Kim, "Experimental study on steel hysteretic column dampers for seismic retrofit of structures," *Steel and Composite Structures*, vol. 40, no. 4, pp. 495-509, 2021.

[11] M. Ito, Y. Murata, K. Hoki, and M. Nakashima, "Online hybrid test on buildings with stud-type damper made of slitted steel plates stiffened by wood panels," *Procedia Engineering*, vol. 14, pp. 567-571, 2011.

[12] G. Xu, T. Guo, A. Li, S. Wang, R. Zhang, R. Zhu, and J. Xu, "Review on self-centering damper for seismic resilient building structures," in *Structures*, 2023, vol. 54: Elsevier, pp. 58-77.

[13] M. A. Kafi, "The geometric shape effect of steel slit dampers in their behavior," *Magazine of Civil Engineering*, no. 3 (87), pp. 3-17, 2019.

[14] Y. Liu, Z. Guo, X. Liu, R. Chicchi, and B. Shahrooz, "An innovative resilient rocking column with replaceable steel slit dampers: Experimental program on seismic performance," *Engineering Structures*, vol. 183, pp. 830-840, 2019.

[15] J. Yang, S. Liang, X. Zhu, L. Dang, T. Shen, and S. Zhou, "Experimental and theoretical research on a shear-bending-metallic-damper with a double-phased yield mechanism," *Journal of Constructional Steel Research*, vol. 203, p. 107839, 2023.

[16] A. Cheraghi and S. M. Zahrai, "Cyclic testing of multilevel pipe in pipe damper," *Journal of Earthquake Engineering*, vol. 23, no. 10, pp. 1695-1718, 2019.

[17] S. L. Mahyari, H. T. Riahi, and M. Hashemi, "Investigating the analytical and experimental performance of a pure torsional yielding damper," *Journal of Constructional Steel Research*, vol. 161, pp. 385-399, 2019.

[18] A. Ghadami, A. Ghamari, and R. P. Jaya, "Improving the behavior of the CBF system using an innovative box section damper: Experimental and numerical study," in *Structures*, 2024, vol. 62: Elsevier, p. 106210.

[19] J. Wang, J. Men, Q. Zhang, D. Fan, Z. Zhang, and C.-H. Huang, "Seismic performance evaluation of a novel shape-optimized composite metallic yielding damper," *Engineering Structures*, vol. 268, p. 114714, 2022.

[20] M. G. Gray, *Cast steel yielding brace system for concentrically braced frames*. University of Toronto (Canada), 2012.