An Investigation of an Innovative Diagonal Brace-Brake Pad Friction Damper via Experimental and Numerical Methods

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Abstract:

Earthquakes represent a considerable hazard to braced steel frames, thereby underscoring the necessity for economically viable mitigation strategies. Braced steel frames are extensively employed in construction owing to their exceptional strength and rigidity. Nevertheless, their intrinsic stiffness may result in substantial damage during seismic occurrences. This investigation examines a potentially effective solution: brake pad friction dampers. A comprehensive experimental-numerical analysis is presented to evaluate their energy dissipation properties. An experimental assessment under cyclic loading is conducted to ascertain the performance of individual damper components. Finite element simulations employing ABAQUS and OPENSEES scrutinize the efficacy of such dampers when incorporated into diagonal brace braced frames subjected to seismic forces. This research endeavors to elucidate the seismic performance of brake pad friction dampers in diagonal braced, with an emphasis on their capacity to enhance seismic performance. The findings bear significant potential for the formulation of innovative and cost-efficient solutions for earthquake-resistant infrastructures. Furthermore, to augment the comprehension of seismic performance enhancement, a numerical study is performed to quantify the Response Modification Factor. The influence of the friction brake pad (FBP) on the R factor of brace-friction damper structural systems is analyzed through push-over assessment. Subsequent investigations will explore optimal damper design parameters and specifications, including a range of damper capacities.

Keywords:

diagonal-braced frames; Seismic mitigation; Brake pad friction damper; Cyclic loading; Experimental examination; Numerical analysis; Brace-friction damper structural system.

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1.Introduction

Researchers have conducted extensive examinations of various control mechanisms that have been implemented across an array of structural forms. The systems proposed encompass energy-dissipating devices, base isolators, as well as both active and hybrid methodologies. These pioneering devices are designed to reduce inter-story displacements and alleviate structural damage. Conventional building regulations prioritize the design of structures that can endure moderate seismic events with minimal damage while simultaneously preventing structural collapse during significant seismic occurrences, with a predominant emphasis on safeguarding human life. A primary factor contributing to structural durability is the energy dissipation that occurs during inelastic deformations, resulting in bending, twisting, and cracking[3-24-27-33-35]. The seismic performance of a given structure is significantly influenced by both the energy introduced into the structure and the energy that is dissipated. Consequently, the optimization of seismic responses serves to diminish the disparity between the input energy and the energy dissipated[33]. Among the various seismic dissipation devices, hysteretic dampers are particularly esteemed for their straightforward design and economic efficiency[14].

In 1980, an innovative methodology aimed at reducing structural energy absorption through the utilization of frictional dampers was unveiled[31]. This study introduced Limited Slip Bolted (LSB) joints that were specifically engineered to dissipate energy at the junctions of extensive panel structures. A series of comprehensive static and dynamic evaluations were performed to validate the system's consistent and predictable frictional characteristics, emphasizing not solely maximum energy dissipation but also the repeatability of the results.

Subsequently, Pall and Marsh empirically established that the hysteresis response of sliding friction joints exhibited a high degree of consistency, efficiency, and an almost rectangular shape. Furthermore, the performance of these joints remained stable even after multiple loading cycles, effectively enduring successive seismic events[29]. Their research indicated that optimizing the tuning of sliding friction joints could significantly enhance the system's resilience to seismic forces.

Mualla and Belev [29] introduced a groundbreaking study centered on the seismic response of steel frames that were integrated with an innovative friction damper device, functioning as part of a passive control system. This study included exhaustive testing to assess the performance of the friction pad material, evaluate damper unit efficiency, and analyze the response of scaled model frames subjected to lateral excitation.

Another investigation proposed a clamping arrangement utilizing high-strength bolts to evaluate the performance of friction pads. Experimental assessments were carried out on diverse friction pad specimens to ascertain the mechanical properties within the friction interface region[34].

The slip load constitutes a vital determinant in the efficacy of friction dampers. Research efforts have delved into the control of seismic response within a steel moment-resisting system equipped with a friction damper characterized by two slip loads during seismic excitations[15].

Diagonal bracing represents a traditional earthquake-resistant framework, and the integration of this system with dampers has demonstrated reliability and advantages. The behavior of a specifically developed friction damper composed of steel strips and high-strength steel bolts implemented in diagonal bracing has been thoroughly investigated, with a particular focus on earthquake-induced damage in welded joints[28].

Recent investigations have underscored the implementation of chevron bracing in conjunction with a horizontal friction brake pad damper, primarily attributable to the complications associated with non-rigid connections. A combination of numerical simulations and empirical studies has been executed in this domain[22].

Subsequent inquiries have assessed the implications of employing Friction Brake Pad (FBP) dampers within steel frameworks featuring chevron braces[22]. These investigations encompassed the utilization of corner sheets for the fabrication of dampers, alongside conducting experimental evaluations of the mechanical characteristics of steel friction pads utilized in rotational friction dampers[34]. Furthermore, a parametric analysis was performed to scrutinize the seismic response of knee-braced frameworks equipped with friction dampers[14].

In order to assess the impact of friction dampers on the seismic performance of braced frameworks, this research encompasses an examination of the calculation of the response modification factor. Given the critical importance of the response modification factor in seismic design, numerous researchers have engaged in the estimation of the R factor across various structural systems.

The NEHRP Recommended Provisions commentary delineates the R factor as an empirical response modification factor intended to encapsulate the damping and ductility characteristics of a structural system when subjected to displacements nearing its maximum threshold. This definition elucidates the qualitative understanding that developers possess regarding seismic responses of buildings and the expected behavior of code-compliant structures during seismic events[37].

In a particular study, an evaluation of overstrength, ductility, and response modification factors in special moment-resisting frames integrated with TADAS has been conducted[26].

One prevalent methodology for estimating the R factor is the push-over approach. The response modification factor for steel moment-resisting frames has been appraised through various push-over analysis techniques[19].

Recent advancements in seismic retrofit and damping systems have led to the proposal of several novel damper designs. For instance, Garmeh et al. [12]. introduced and numerically evaluated a rotational damper utilizing hourglass-shaped steel pins, showing significant potential for energy dissipation and ease of replacement[1]. Similarly, their subsequent study on SMA-based self-centering eccentrically braced frames with vertical links demonstrated considerable improvements in recentering capacity and hysteretic performance [13]. These innovations highlight the critical role of hybrid and replaceable damping systems in modern structural engineering[2].

The accurate assessment of damper behavior under seismic loading often necessitates a synergy between experimental observations and advanced numerical models. Hojatkashani and colleagues have contributed extensively to this domain, exploring the fatigue performance of CFRP-retrofitted RC beams through experimental and finite element approaches [17], and conducting interfacial stress analysis in damaged regions [18]. These studies provide a robust foundation for validating damping performance under cyclic and high-cycle loading scenarios.

This investigation employs a synergistic experimental and numerical approach to assess the efficacy of brake pad friction dampers in mitigating seismic damage in diagonal-braced. The experimental component encompasses cyclic loading tests on individual damper elements to evaluate their performance. Finite element simulations executed via ABAQUS and OPENSEES analyze the performance of these dampers when integrated into diagonal-braced under seismic conditions. The objective of the research is to elucidate the seismic performance of brake pad friction dampers, highlighting their potential to diminish structural damage.

Ultimately, the fundamental and innovative aspect of the present research will be articulated as the appraisal of the R factor for brace-friction damper structural systems.

2. Concept and Techniques of Friction Dampers

The concept of friction fundamentally derives from Coulomb's foundational principles. The magnitude of the frictional force is commonly expressed by the equation[14-31]:

$$F = \mu . N \quad (1)$$

where (F) represents the frictional force, (N) is the normal force, and (\mu) denotes the coefficient of friction. This coefficient is influenced by the nature of the interacting surfaces. Typically, an object with weight (W) will start to move when the applied lateral force (P) exceeds the frictional resistance (F), as depicted in Fig. 1.

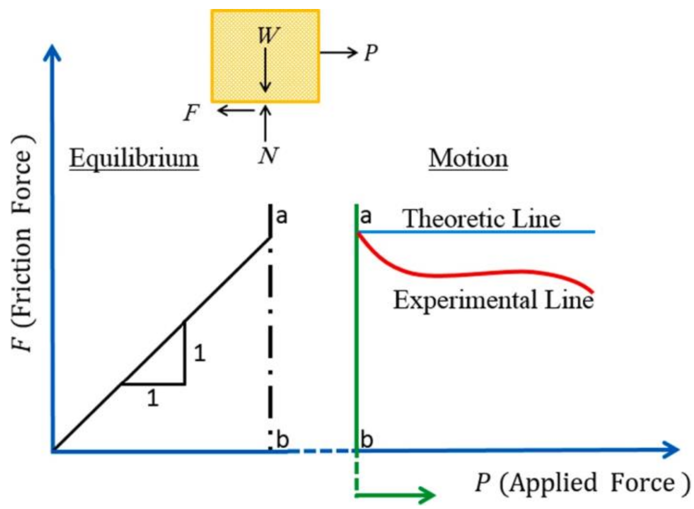


Fig. 1. Relationship of the frictional force with the applied force[12].

Friction is a complex phenomenon mainly associated with the dissipation of energy. During this process, part of the energy is lost through viscous effects, while other components dissipate due to adhesion and surface interactions. Ultimately, the energy lost through friction converts kinetic energy into potential and thermal energy[1].

In structural engineering, dampers are classified based on their methods of energy dissipation and their specific applications within buildings. Such devices include friction dampers, rotational dampers, and brake pad dampers, each characterized by unique operational and structural attributes[20]. These dampers can be integrated into structures in various configurations, such as cross-bracing, chevron, or diagonal systems, each requiring tailored design considerations[9].

3. FBP Damper

Friction dampers employ dry friction to absorb and dissipate vibrational energy, thus limiting the response of a structure. These devices function by maintaining contact between two surfaces in relative motion, generating frictional resistance. The Horizontal Friction Brake Pad (FBP) is a unidirectional friction damper designed to reduce linear relative displacement between planar surfaces within a frequency range of 10 Hz to 1 kHz[11].

FBP dampers are capable of efficiently dissipating a substantial portion of seismic energy input, contributing to the overall safety of the structure. To ensure consistent performance during seismic and cyclic loadings, it is crucial to provide sufficient slip resistance at the contact surfaces and to accommodate displacement and movement within the damper[33]. Previous investigations have examined the application of FBP dampers in chevron, knee, and cross-bracing configurations.
This study focuses on experimentally and numerically evaluating the response of steel frames equipped with diagonal braces fitted with FBP dampers. The damper's design is optimized for straightforward installation within diagonal bracing systems, enhancing the structure's strength and energy dissipation capacity against seismic actions.

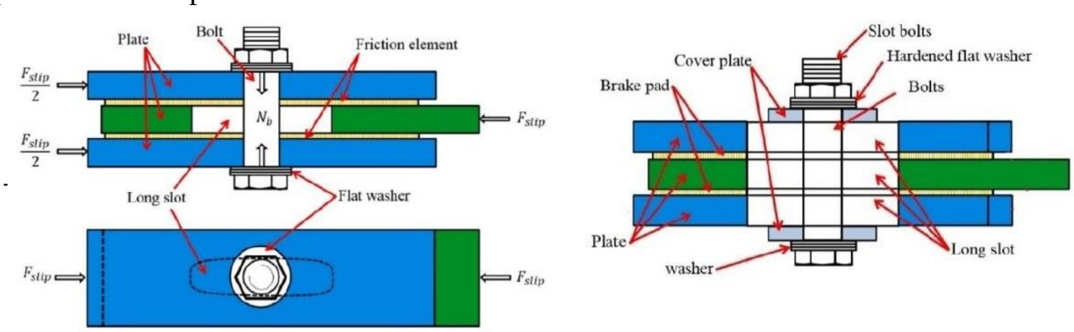
The damper consists of a housing with internal movable plates. During seismic activity, friction between the steel plates and brake pads converts vibrational energy into heat, thus dissipating it effectively. Additional details of the experimental setup are outlined in the subsequent section.

4. Experimental Program and Test Setup

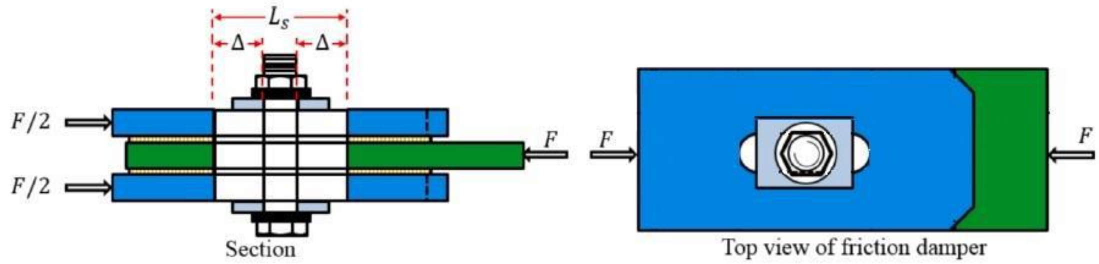
This study centers on the evaluation of friction dampers equipped with brake pads. To validate and scrutinize the damper's key parameters, comprehensive cyclic loading tests were performed on its components. Additionally, parametric analyses and assessments of the component's integration within diagonal bracing systems were conducted through numerical simulations.

Figure 2 illustrates a typical configuration of a slotted bolted connection (SBC). It is important to note that the core concept of the innovative damper introduced here aligns with the details depicted in this figure. As shown, such connections can withstand numerous energy dissipation cycles with minimal or no structural damage. The friction necessary for energy dissipation in these connections is derived from the pre-tensioning force applied by the bolts. A slip bolt connection engineered for energy dissipation must be capable of repeated displacement cycles without losing resistance, stability, or dissipative capacity. The efficiency of SBCs relies on several key factors[6]:

1. Maintaining consistent compression between the sliding plates (achieved through springs and flat washers);
2. Ensuring a uniform slip coefficient between the plates (by selecting appropriate slip elements);
3. Avoiding brittle failure of connection components near the slip threshold (by choosing suitable bolt materials).



(a)



(b)

Fig. 2. Detail of experimental specimen of friction damper with brake pad[12]. (a) Damper details including friction surfaces (regarding the details mentioned in); (b) top view for the build experimental specimen.

According to Fig. 2, the friction force in the SBC is expressed as:

$$F\text{slip}=n\cdot a\cdot \mu\cdot Nb \quad (2)$$

where:

- a is the number of friction plates,
- n is the number of bolts,
- Nb is the tensile force in each bolt, and
- μ is the friction coefficient.

The friction damper examined in this research is a type of friction brake pad (FBP), which features slotted holes on the sides of its housing. High-strength bolts apply the necessary tensile force to generate friction during slippage. Figure 2 also details various components of the FBP, including steel sheets, washers, bolts, brake pads, and the housing box. Notably, the box includes elongated slotted holes with a length of Ls=25mm.

The geometry and 3D schematic of the tested damper component are presented in Figure 3. To improve the frictional performance and energy dissipation capacity, brake pad elements—composed of materials such as carbon, steel, polymer fibers, and other additives for enhanced abrasion resistance—are placed at the interface between the box sides and steel plates. Cyclic loading was applied to the FBP using a Universal Testing Machine (UTM).

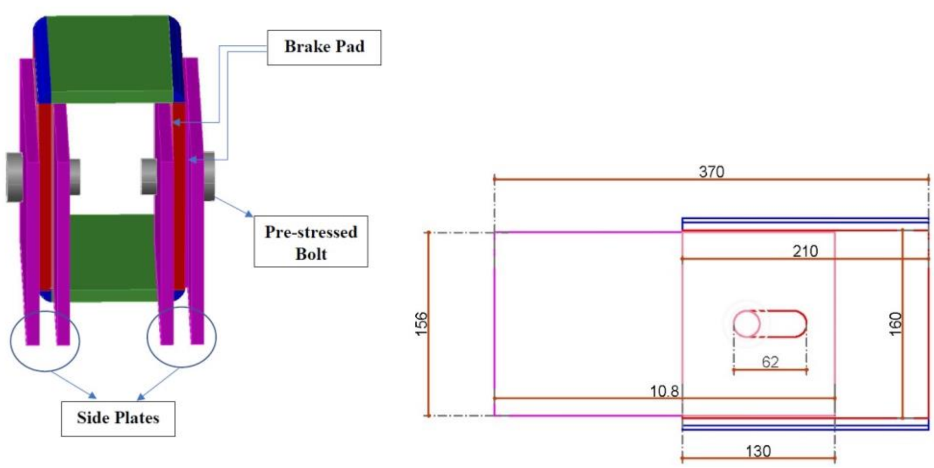


Fig. 3. (a) Schematic 3D shape of the FBP damper, (b) Geometry and details of section view of the damper (dimensions are in mm).

The experimental setup is detailed in Figure 4, with the loading protocol outlined in Figure 5 and summarized in Table 8. Regarding the loading schedule in Figure 5, it is noteworthy that the selection of the slotted bolt connection was based on the method outlined by Loo et al. (2014) [25]. The analysis employed a Static Stress/Displacement approach, with displacement histories adopted from Loo et al.'s testing of SBC connections. This protocol was applied consistently to both the numerical simulations and physical experiments, enabling the extraction of the structural response and the development of a behavioral model for the FBP.

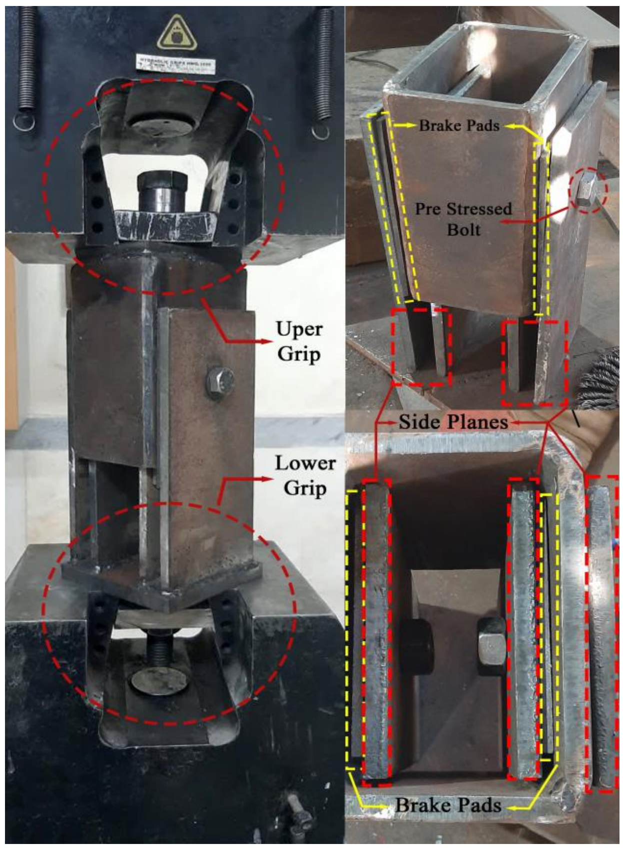


Fig. 4. (a) Descriptive illustration of the damper components, (b) Experimental specimen and test setup for cyclic test of the damper (Images by Mehdi Shalchi Toosi).

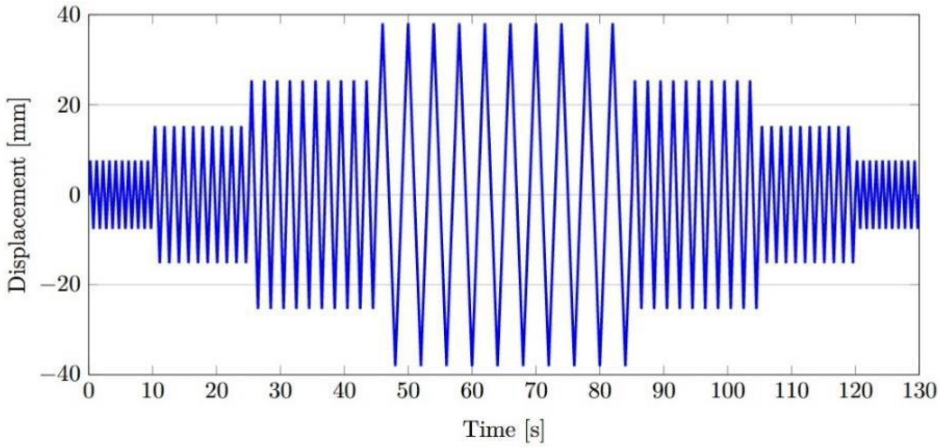


Fig. 5. Full displacement-time history[21].

5. Concept of frictional connection with slotted holes

Flat brake pads made from ST37 steel—similar to conventional automotive brake pads—are employed to generate friction for energy dissipation in the damper. These pads are clamped between steel plates using high-strength bolts that require pre-tensioning to establish the necessary frictional resistance.

The damper's main housing comprises welded plates joined via fillet welds. Inside the housing, four strategically placed plates are incorporated to mitigate buckling effects, with their lengths optimized to minimize such risk. These interior plates are bolted to the housing, and four flat brake pad sheets are inserted both inside and outside the box, positioned between steel plates to ensure consistent frictional contact with the longitudinal steel elements.

For testing purposes, two steel caps can be welded at opposite ends of the damper. These caps serve as attachment points for the servo machine grips, enabling the application of cyclic loads to evaluate the damper's performance under dynamic conditions.

6. Materials and elements specifications

The main components of the damper examined in this study include plates, bolts, and brake pads. The material specifications for these parts are provided in Tables 1 and 2.

Table 1. Materials specifications

Component	Steel type	F_y (MPa)	F_u (MPa)	F_y/F_u	Elongation (%)
Box and plates	ST 37	295	415	0.71	28
Bolt	M20	-	800	-	-

Table 2. Material specifications

Component	Consistent material	Poison ratio	Friction ratio	Modulus of elasticity (MPa)
Brake Pad	Chrysotile	0.25	0.36	2.2 e 5

When analyzing frictional behavior, it is essential to distinguish between two types: (1) the friction between the bolt and steel plate, and (2) the friction between the brake pad and steel surface. Existing research indicates that the dominant frictional behavior stems from the sliding of steel plates, while the friction involving the brake pad depends on the specific pad material and its interaction with steel surfaces. These frictional characteristics can be experimentally determined and subsequently incorporated into numerical models.

The bolts used for assembling the damper are M20 high-strength HR-type bolts, classified as Group A325 according to EN 14399-3 and EN 14399-4 standards[7-8]. These bolts are specifically designed for pre-tension applications, ensuring reliable performance under cyclic loading conditions.

7. Loading procedure

The experimental testing employed the full loading protocol, while for the numerical analysis, a simplified, truncated displacement schedule with a limited number of load cycles was used[25-36]. Cyclic loading was applied to the specimen using a Universal Testing Machine (UTM), which consisted of a single bolt on each side to facilitate the test.

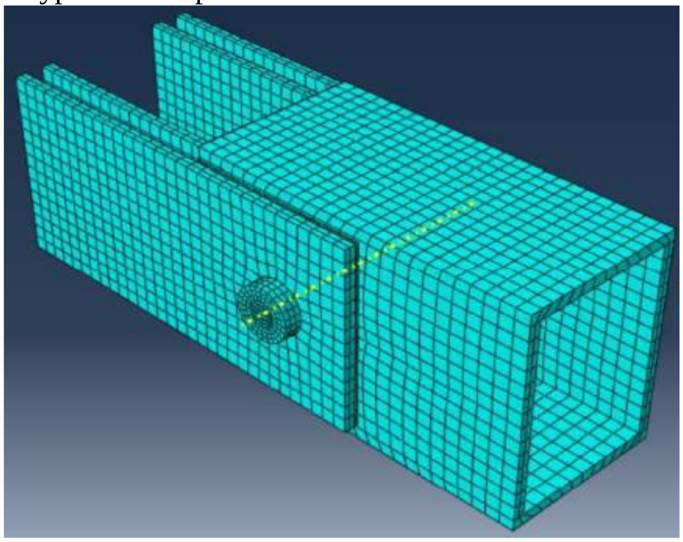
8. Numerical analysis

Analysis of the FBP component
In this study, finite element analysis (FEA) was performed using ABAQUS. The numerical results were compared with the experimental findings to validate the modeling accuracy. Detailed information on the modeling approach is provided below. To ensure result reliability and accuracy, a mesh sensitivity study was conducted as part of the validation process.

The design and modeling methodology for the current damper closely follows the approach outlined by Terblanche [36], which focused on the structural behavior of slotted bolted friction connections. Building upon this analytical framework, the concept of the current FBP damper was developed.

A parametric study was carried out to assess the damper's effectiveness, examining how different parameters influence performance. These included the number and arrangement of side bolts, as well as the thickness of the attached plates. Throughout the analysis, a uniform brake pad thickness of 5 mm was maintained across all specimens. The specimens are designated accordingly.

As shown in the results section, variations in the thickness of the side plates have a negligible effect on the overall capacity and the hysteresis patterns of the dampers. Conversely, the number of pre-tension bolts significantly influences the damper's behavior. Based on this, three types of dampers are introduced, and their ABAQUS models are illustrated in Figure 6.



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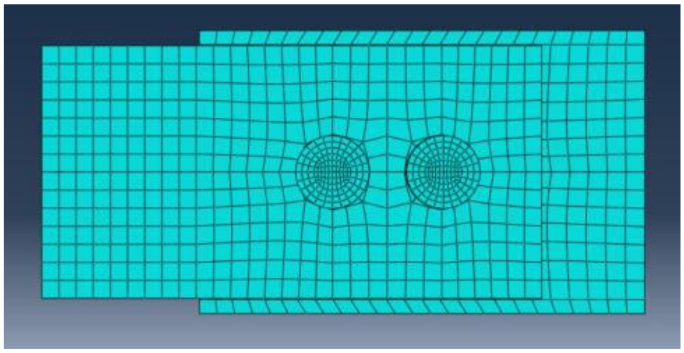

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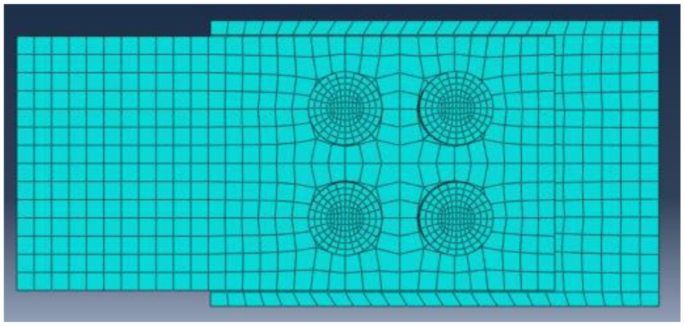

(c)

Fig. 6. Meshing patterns of the friction dampers. (a) Damper component type A; (b) Damper component type B; (c) Damper component type C.

9. Examination of the performance of FBP damper in a single frame

The FBP damper was integrated into a diagonal-braced frame for this study. The frame's specifications and force-displacement diagram are detailed in references[5]. Figure 7 illustrates the studied diagonal-braced structure. Additionally, the performance of the FBP damper within the frame was analyzed using OPENSEES, considering various damper configurations.

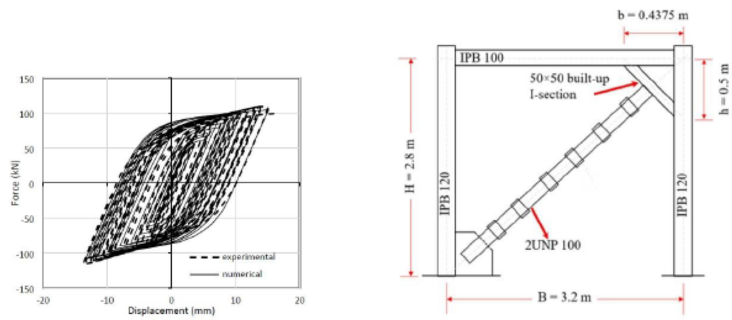

Fig. 7. Detail of the frame and force-displacement diagram[5].

Proposed locations for installing the damper within the frame are shown in Figure 8. One position is at the junction where the brace connects to the column, with a gusset plate linking the damper to the column. This configuration creates a series connection between the damper and brace, satisfying the seismic performance requirements of the structural system. This setup benefits from three key aspects: the stiffness of the diagonal element, the stiffness of the brace element, and the damping capacity of the FBP damper. The configuration in Fig. 8a exemplifies the series case, where these elements work in series.

Fig. 8. Positions of the damper in KBF-damper system. (a) Series condition; (b) Parallel condition.

The second proposed location, shown in Fig. 8b, positions the damper behind and attached to the diagonal element. This arrangement illustrates a parallel configuration of the structural elements, offering an alternative damping-enhanced response.

10. Results discussion

Verification of the FBP damper component with experimental

In the verification phase of the parametric study, specimen 1 was employed as the primary sample. As detailed earlier, this specimen consisted of a single high-strength, pre-tensioned A325 bolt on each side of the damper assembly. The specimen was subjected to uniaxial testing, following the cyclic loading protocol described previously. A finite element (FE) model was developed in ABAQUS to simulate this component, incorporating nearly all the experimental parameters, including the significant pre-tension forces in the bolts and the frictional interactions between brake pads and side steel plates.

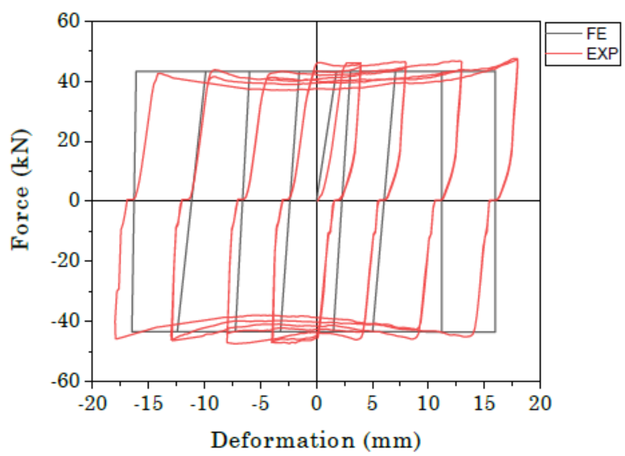

Fig. 9. Comparison of load-deformation diagrams for FE analysis and experimental test of the damper specimen 1, type A.

Regarding the force-deformation behavior of the FBP under cyclic loading, Figure 9 presents a comparison between the ABAQUS FE analysis results and the experimental data obtained via a Universal Testing Machine (UTM), as referenced in Section 4. The FE analysis indicated a maximum damper capacity, based on the average slip force, of approximately F_{slip}=43kN. The hysteresis loops from the numerical analysis align closely with the experimental results, which were obtained using the previously discussed displacement schedule. This confirms that the brake lining provides adequate elastoplastic properties in symmetric connections.

11. Comparative Analysis of FBP Damper FE Models

Numerical simulations using ABAQUS were performed for all specimens listed in Table 3, with results illustrated in Figure 10.

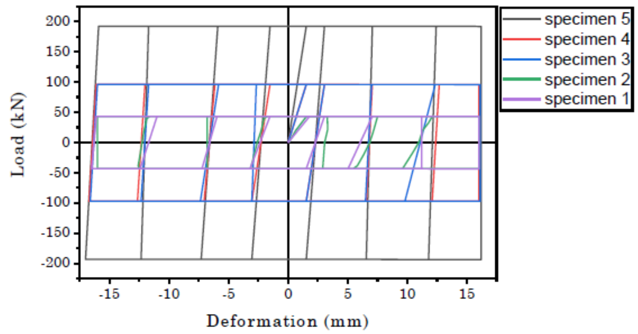

Fig. 10. Comparison of load-deformation diagrams for FE analysis of FBP models.

Analysis reveals that a minor 2mm alteration in the side plates slightly influences the damper's capacity and energy dissipation across all configurations with identical pre-tensioned bolt layouts. Nonetheless, the critical factor is the quantity and arrangement of pre-tensioned bolts; increasing the number of bolts substantially enhances damping capacity, following the progression from Type A to B and then to C. Furthermore, the initial stiffness leading to the slip point increases progressively as the number of bolts rises—from a single horizontal bolt in specimen 1 to two in specimen 5, with four bolts in total.

Table 3. FBP models for the parametric study

Model	Type	Number and pattern of Bolts	Thickness of side plates (mm)
Specimen 1	A	1 bolt	10
Specimen 2		1 bolt	8
Specimen 3	B	2 bolts horizontally	10
Specimen 4		2 bolts horizontally	8
Specimen 5	C	4 bolts	8

12. Impact of FBP Dampers on diagonal-braced Structural Performance

As summarized in Table 3, the FBP dampers studied are categorized into three types: A, B, and C. Their influence on the braced frame shown in Figure 8 has been assessed here. The braced frame comprises the diagonal element, the brace, and the damper, all contributing to the overall stiffness and damping capacity of the structure. Energy dissipation primarily occurs through the plastic behavior of the diagonal element, whereas the brace operates elastically.

The integration of FBP dampers introduces additional damping, but variations in their capacity—achieved by adjusting bolt arrangement—can either improve or diminish energy dissipation efficiency. Since the damper's capacity depends on the number and configuration of pre-tensioned bolts, these factors influence the interaction among the components. The series connection (Figure 11) indicates that augmenting the damper's capacity enhances the overall frame capacity, with the initial elastic stiffness increasing as the number of bolts grows from a single to multiple bolts, as seen from the hysteresis diagrams.

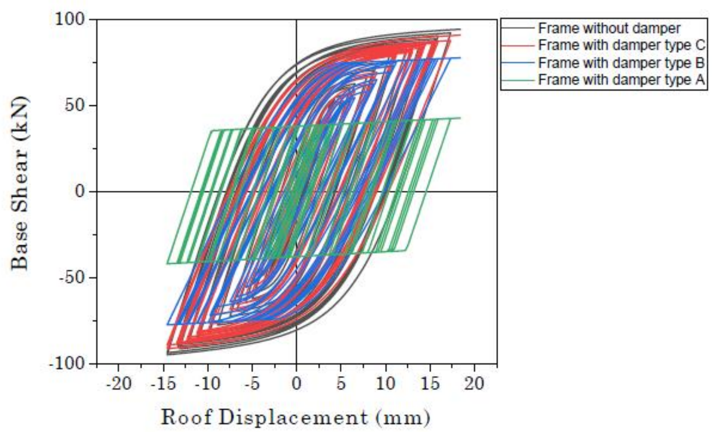

Fig. 11. Base shear Force-roof displacement diagrams from FE analysis for the single KBF equipped with types of FBP dampers, Series condition according to Fig 8a detail.

In contrast, the parallel configuration (Figure 12) exhibits a direct effect on the frame's base shear capacity, with higher-capacity dampers leading to increased maximum forces. Energy absorption capacities, derived from hysteresis loops in Table 4, demonstrate that the parallel arrangement yields higher energy dissipation compared to the series configuration.

Table 4. Energy absorption values for Hysteresis curves resulted from loading of single KBF frame, units are in kN.m

Type of the damper used in the frame	Position of damper is at the base of column, Series case according to Fig 9a detail	Position of damper is behind the knee element, Parallel case according to Fig 9a detail	Ratio of parallel to the series condition
Frame without damper	3.26	3.25	-
Frame with damper type A	1.76	4.92	2.8
Frame with damper type B	2.46	6.66	2.7
Frame with damper type C	2.83	9.192	3.25

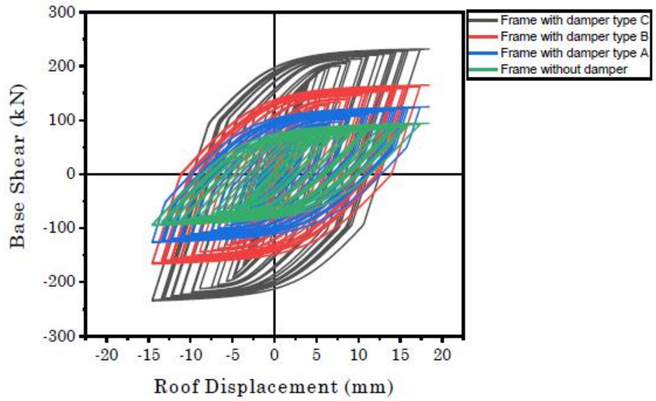

Fig. 12. Base shear Force-roof displacement diagrams from FE analysis for the single KBF equipped with types of FBP dampers, Parallel condition according to Fig 8b detail.

13. Full-Scale Push-Over Analysis of a diagonal-braced Structure with Damper System

To better understand the performance of the diagonal-braced damper system, a three-story building was modeled using OPENSEES. The structure features diagonal-braced as the lateral load-resisting system, with dampers incorporated to assess their impact. The building spans 4 and 6 meters, with a 3D model developed, and a representative 2D frame extracted for detailed analysis. All beams and columns utilized W-section members, with dimensions in inches, as detailed in Figures 13 and Table 5. Push-over analyses were conducted on this 2D frame (see Fig. 13b).

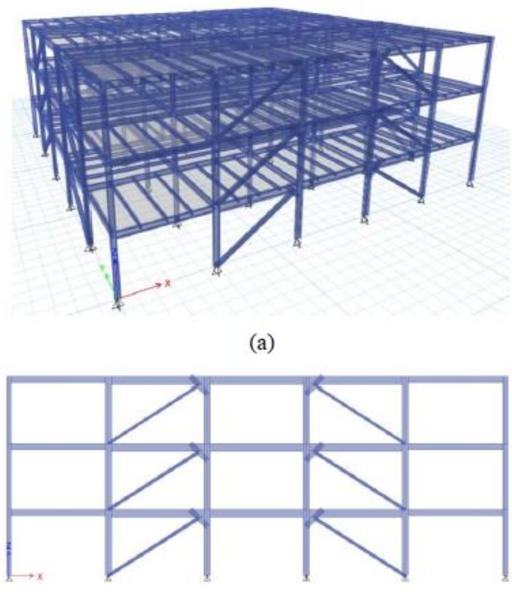

Fig. 13. (a). 3D modelling of a full-scale building, (b) 2D frame of the building structure.

Table 5. Lateral structural system detail

Story	Brace	Knee element	Force capacity for plastic hinge in Knee element (Ton)
Story 1	HSS $9 \times 9 \times \frac{3}{8}$	W 12×58	167.4
Story 2	HSS $9 \times 9 \times \frac{3}{8}$	W 12×58	167.4
Story 3	HSS $8 \times 8 \times \frac{3}{8}$	W 12×40	111.45

A key aspect of this modeling involved selecting damper capacities, based on the plastic capacity of diagonal elements and the configuration of the diagonal-braced damper system in either series or parallel (refer to Figure 8). Ranges of damper capacities were assigned accordingly, with larger values for the series arrangement, consistent with earlier results from Figures 11 and 12. Damper capacities were set as a percentage of the force necessary to initiate plastic hinge formation in the diagonal elements (Table 6).

Table 6. Capacities of dampers in KBF-damper system

Knee element W 12 × 58		Knee element W 12 × 40	
Damper capacity for Series case (Ton)	Damper capacity for Parallel case (Ton)	Damper capacity for Series case (Ton)	Damper capacity for Parallel case (Ton)
133.9	83.7	89.16	55.7

The analysis incorporated concentrated plastic hinges at the diagonals, with moment-rotation behavior modeled using Bilin material properties[23]. This approach captures the post-peak moment drop, influencing the overall push-over curve and structural resistance. The results show a significant increase in the maximum base shear: from approximately 396.6 tons without dampers to about 553 tons with dampers in the parallel configuration. The series arrangement also enhances the base shear, reaching around 404.2 tons, but the parallel setup yields a notable amplification, about 1.4 times that of the nonsystem.

14. Conclusion

This integrated experimental and numerical study evaluates the efficacy of friction dampers embedded in brake pads (FBP) for reducing seismic-induced damage in diagonal-braced steel frames.The research combines cyclic loading tests with finite element analysis to provide comprehensive insights. The finite element modeling of the FBP component was performed using ABAQUS, while the overall performance of the diagonal-braced damper system—both on a scaled model and a full-scale structure—was analyzed with OPENSEES.

Regarding the hysteretic behavior and energy dissipation capacity, as indicated by the loop areas in the hysteresis curves, the following conclusions were drawn:

- Un-damped frames exhibited high load-carrying capacity but negligible damping.
- Damper Type A increased energy dissipation but at the expense of reduced overall frame capacity.
- Damper Type B achieved a balanced performance, enhancing energy dissipation while maintaining acceptable base shear capacity and minimizing pressure on the diagonal elements.
- Damper Type C, despite further increasing energy dissipation, negatively impacted the system's damping effectiveness due to excessive pressure on the diagonal element.

The placement of the damper within the diagonal-braced damper system was identified as a critical factor. The primary components of the lateral structural system damper, brace, and diagonal elements—interact differently depending on damper installation. Specifically, placement at the column base (series configuration) versus behind the diagonal element (parallel configuration) significantly influences the overall system response.

Numerical simulations of a single frame indicated that increasing the damper capacity enhances the energy absorption capability. Notably, for Damper Type C, the energy dissipation in the parallel configuration was approximately 3.25 times greater than in the series arrangement.

Full-scale structural analyses uncovered key findings, particularly regarding the Response Modification Factor (R). The salient results are summarized below:

- Push-over analysis showed that the maximum base shear force for the structure equipped with dampers in the parallel configuration was nearly 1.4 times higher than that of the undamped structure.
- A comparison between the maximum base shear forces in undamped and damped structures (series configuration) revealed minimal difference, although a significant plastic deformation region was observed in the force-displacement response of the series configuration. This suggests that the parallel damper arrangement is more effective than the series configuration in seismic mitigation.
- Furthermore, a novel aspect of this research involved calculating and comparing the *R*-factor. The results demonstrate that the *R*-factor increased from 3.47 (undamped structure) to 5 when employing a parallel-installed damper system. This indicates that integrating the diagonal-braced damper system can enhance the *R*-factor by approximately 1.33 times, signifying improved seismic resilience.

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