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“Meta-Analysis of Cyclic Behavior of Steel Frames with Combined BRB and Friction Dampers: Challenges and Future Directions

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ABSTRACT

This study investigates the cyclic behavior of steel frames equipped with combined Buckling-Restrained Braces (BRB) and friction dampers. With the increasing occurrence of destructive earthquakes worldwide and their impact on urban structures, the need for earthquake-resistant structural design has become more pressing. Steel structures, due to their favorable properties such as high strength-to-weight ratio and ductility, are widely used in construction projects. This study particularly focuses on combined dampers, which can significantly enhance the performance of structures under dynamic and seismic loads. Previous research has shown that the combination of BRB and friction dampers can lead to reduced displacements, improved dynamic performance, and decreased damage to structural members. However, challenges such as the lack of standardized design guidelines, insufficient analytical models, and uncertainties related to damper behavior still exist. Using a meta-analytical approach, this study collects and analyzes existing data from reputable databases to identify the challenges and future directions in this field. The results indicate that combined dampers can serve as effective tools for improving the seismic safety of structures. Furthermore, the study emphasizes the need for additional research on the long-term effects and fatigue induced by cyclic loads on dampers. This study is proposed as a reliable reference for researchers and engineers in designing and improving the seismic performance of steel structures.

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1. Introduction

In recent years, with the increasing frequency of destructive earthquakes in different regions and their effects on urban structures, the need for earthquake-resistant design has become more evident. Steel structures, due to their advantageous properties such as high strength-to-weight ratio and ductility, are extensively employed in construction projects. One of the main challenges in designing steel structures is controlling their dynamic behavior under seismic loads. This challenge has prompted research into the use of dampers as effective tools to enhance the performance of steel structures (Esfandiari & Khezeli, 2019).

In this context, combined dampers, particularly Buckling-Restrained Braces (BRB) and friction dampers, have been identified as suitable options for improving the cyclic behavior of structures. BRB dampers, due to their energy dissipation capability and reduction of structural displacements, perform particularly well under severe earthquakes (Auricchio et al., 2011). On the other hand, friction dampers help reduce transmitted forces to the structure, contributing to overall improved structural performance. However, using these two types of dampers in combination requires further investigation regarding their cyclic behavior and interaction under varying conditions.

Previous studies have demonstrated that combining BRB and friction dampers can enhance structural performance under dynamic loads and reduce damage to structural members (Zanganeh, 2021). Nevertheless, specific challenges remain, including the nonlinear and complex effects of these dampers on structural behavior under different loading conditions. Such uncertainties and complexities can create difficulties in design and prediction, necessitating more in-depth research (Moradi & Tavakoli, 2019). Another challenge is the lack of standardized guidelines for designing steel structures with combined dampers. The absence of comprehensive analytical models capable of accurately simulating damper behavior under dynamic loads presents further complications (Rahimi et al., 2022). This makes the selection and design of dampers particularly challenging, especially in large and complex projects.

Furthermore, there is a need for a deeper understanding of the long-term effects and fatigue caused by cyclic loads on combined dampers. This is especially significant when structures are subjected to repeated and severe loading (Sultana & Youssef, 2018). Meta-analytical studies can help gather and analyze existing data on the cyclic behavior of these dampers and lay the foundation for future research.

Additionally, better understanding of the interaction between the cyclic behavior of BRB and friction dampers and their effects on overall structural performance can improve the design and efficiency of such structures. This is particularly relevant in seismic regions, contributing to enhanced safety and reduced damage during severe earthquakes (Kitayama & Constantinou, 2016). Therefore, research in this field is recognized as a fundamental requirement in earthquake engineering.

Accordingly, the main objective of this study is to conduct a comprehensive meta-analysis of the cyclic behavior of steel frames equipped with combined BRB and friction dampers. This study analyzes existing research data to identify the challenges and future directions in this area. The

results can ultimately contribute to improving the design and seismic performance of steel structures, providing effective solutions for structural engineers.

3. Research Methodology

The research methodology of this study is a systematic review aimed at analyzing and collecting data regarding the cyclic behavior of steel frames with combined BRB and friction dampers. The study is based on indexed articles in reputable scientific databases including Springer, Google Scholar, Elsevier, CIVILICA, and four Iranian university databases (SID) (Chen et al., 2020). The documents were collected from Spring 2021 to Fall 2024, aiming to provide a comprehensive overview of advances and challenges in this field.

Specific keywords such as “BRB damper,” “friction damper,” and “Cyclic Response of Steel Structures” were used to search titles and abstracts of articles. Out of more than 200 articles mentioning “damper,” 50 focused on “friction damper,” and 42 addressed “Improving the Cyclic Response of Steel Structures,” unrelated and duplicate articles were removed (Kholghifard & Badakhshan Nejad, 2021). The remaining full-text articles were carefully reviewed, and those directly relevant to the research topic were identified.

Data and results from the selected articles were categorized in a database for analysis (Moarrab et al., 2020). This categorization included qualitative and quantitative analyses of the cyclic behavior and performance of BRB and friction dampers in steel frames. To ensure quality and validity, only articles published in reputable scientific journals with sufficient citations were included, increasing the credibility and reliability of the findings.

The study also considered the geographical and thematic diversity of the articles to achieve comprehensive and reliable conclusions. Finally, the collected data were systematically analyzed, and results were presented in terms of challenges and future directions for designing and implementing combined BRB and friction dampers in steel frames. These results can serve as a reliable reference for researchers and structural engineers aiming to improve the seismic performance of steel structures. The ultimate goal of this study is to identify and clarify key points and challenges in the cyclic behavior and performance of dampers.

4. Results

The following table presents the results of the study on the cyclic behavior of steel frames with combined BRB and friction dampers, with detailed analysis for each topic.

(Note: The table was referenced in the original text but not provided; it can be added here in the final manuscript.)

Table 1 . Results Obtained from the Review of Previous Studies

Results / Effects	Topic
Reduction of structural displacements: BRB dampers effectively reduce structural displacements under seismic loads.	Performance of BRB Dampers
<ul style="list-style-type: none"> • Energy dissipation: High energy dissipation capability, reducing force transmission to structural members. 	
<ul style="list-style-type: none"> • Damage reduction: Decreases damage to structural members and load-bearing elements during severe earthquakes. 	
<ul style="list-style-type: none"> • Fatigue resistance: Good resistance to fatigue caused by cyclic loading. 	
<ul style="list-style-type: none"> • Consistent performance: Maintains appropriate performance under repeated and severe loading conditions. 	
<ul style="list-style-type: none"> • Earthquake force reduction: Significantly reduces seismic forces transmitted to the structure, enhancing structural safety. 	Benefits of Friction Dampers
<ul style="list-style-type: none"> • Improved occupant comfort: Reduces vibrations and shaking, improving occupant comfort. 	
<ul style="list-style-type: none"> • Adjustability: Ability to tune damper properties to meet specific project requirements and structural needs. 	
<ul style="list-style-type: none"> • Reduced maintenance costs: Lowers repair and maintenance costs due to decreased structural damage. 	
<ul style="list-style-type: none"> • Performance under various conditions: Adaptable to different loading types and environmental conditions. 	
<ul style="list-style-type: none"> • Enhanced cyclic load performance: Combined dampers perform better under cyclic loading. 	Cyclic Behavior Analysis
<ul style="list-style-type: none"> • Accurate simulation: Numerical simulations show overall improved structural behavior under dynamic conditions. 	
<ul style="list-style-type: none"> • Reduction of internal stresses: Reduces internal stresses in structural members due to proper force distribution. 	
<ul style="list-style-type: none"> • Damage prediction: Ability to predict potential damage to structural members under abnormal loading. 	
<ul style="list-style-type: none"> • Dynamic analysis: Requires advanced dynamic analyses for accurate evaluation of structural behavior. 	
<ul style="list-style-type: none"> • Lack of standards: Absence of specific design standards for combined dampers in the industry. 	Design Challenges
<ul style="list-style-type: none"> • Limited engineer experience: Limited experience of engineers in designing and using combined dampers. 	
<ul style="list-style-type: none"> • Design complexity: Complexities in design due to interactions between different dampers and structural members. 	

<ul style="list-style-type: none"> • Insufficient data: Lack of experimental and analytical data for precise damper behavior assessment. 	
<ul style="list-style-type: none"> • Need for training: Requirement for training engineers and designers on the use of combined dampers. 	
<ul style="list-style-type: none"> • Fatigue effects on performance: Impact of fatigue from cyclic loads on damper and structural performance. 	Fatigue and Variations
<ul style="list-style-type: none"> • Long-term analysis: Need for long-term studies to evaluate fatigue effects on dampers and steel structures. 	
<ul style="list-style-type: none"> • Identification of weaknesses: Detecting potential weaknesses in damper design and materials over time. 	
<ul style="list-style-type: none"> • Development of new materials: Necessity to develop materials with improved fatigue resistance properties. 	
<ul style="list-style-type: none"> • Accurate modeling: Requirement for precise modeling of damper fatigue behavior under cyclic loading. 	
<ul style="list-style-type: none"> • Overall structural performance improvement: Enhancing overall structural performance by combining BRB and friction dampers. 	Damper Interactions
<ul style="list-style-type: none"> • Maximum force reduction: Minimizing seismic forces and internal stresses through effective damper interaction. 	
<ul style="list-style-type: none"> • Multi-factor behavior analysis: Need for multi-factor analyses to examine interactions between dampers. 	
<ul style="list-style-type: none"> • Interaction modeling: Accurate modeling of interactions among different dampers under various loadings. 	
<ul style="list-style-type: none"> • Integrated design: Integrated design of dampers and structural members for optimized performance. 	Importance in Seismic Regions
<ul style="list-style-type: none"> • Enhanced structural safety: Emphasis on using combined dampers to improve seismic safety. 	
<ul style="list-style-type: none"> • Damage mitigation: Reducing earthquake-induced damage, especially in high-risk areas. 	
<ul style="list-style-type: none"> • Accurate seismic prediction: Precise prediction of earthquake effects on structures using appropriate dampers. 	
<ul style="list-style-type: none"> • Government and regulations: Need for governmental support and regulations to encourage the use of combined dampers. 	
<ul style="list-style-type: none"> • Public awareness: Raising public awareness about structural safety and modern techniques. 	Analytical Models
<ul style="list-style-type: none"> • Need for numerical models: Development of numerical models for precise damper behavior simulation. 	
<ul style="list-style-type: none"> • Nonlinear analyses: Use of nonlinear analyses to study damper behavior under dynamic loading. 	
<ul style="list-style-type: none"> • Advancement of techniques: Enhancing modeling and simulation techniques to improve prediction accuracy. 	

<ul style="list-style-type: none"> • Development of analytical tools: Creating analytical tools to assess damper performance under various conditions. 	
<ul style="list-style-type: none"> • Multiple simulations: Conducting multiple simulations to examine damper behavior under different scenarios. 	
<ul style="list-style-type: none"> • Design guideline development: Focus on developing design guidelines for optimal use of combined dampers. 	Future Research Directions
<ul style="list-style-type: none"> • Experimental verification: Need for experimental studies to validate simulation and analytical results. 	
<ul style="list-style-type: none"> • New material development: Research on developing new materials with improved properties. 	
<ul style="list-style-type: none"> • Long-term analyses: Conducting long-term studies to assess damper behavior over time. 	
<ul style="list-style-type: none"> • Design innovation: Encouraging innovation in designing and implementing new and optimized dampers. 	
<ul style="list-style-type: none"> • Importance of combined dampers: Emphasis on the role of combined dampers in steel frame design. 	Overall Findings / Conclusions
<ul style="list-style-type: none"> • Improvement suggestions: Providing recommendations to enhance damper performance and structural design. 	
<ul style="list-style-type: none"> • Awareness raising: Increasing awareness of modern techniques in earthquake engineering and structural design. 	
<ul style="list-style-type: none"> • Sustainable development: Focusing on sustainable practices and modern techniques in structural design. 	
<ul style="list-style-type: none"> • Support for engineers: Supporting engineers and designers in implementing advanced dampers in projects. 	

5. Results

The results of Table 1 are derived from an extensive analysis of existing literature on the cyclic behavior of steel frames equipped with combined BRB and friction dampers. The findings generally identify the advantages, challenges, and future directions in the design and application of these dampers in steel structures.

One of the most significant outcomes of this study is the positive impact of BRB dampers on the performance of steel structures under dynamic loads. Studies indicate that BRB dampers effectively dissipate seismic energy and prevent its transfer to the structure (Zanganeh & Esfandiari, 2021). This capability leads to reduced structural displacements and consequently, lower damage to structural members. Moreover, the use of friction dampers in combination with BRB dampers has been identified as an effective approach. This combination can improve the overall structural performance under dynamic loads and reduce internal stresses (Esfandiari & Khezeli, 2019).

Cyclic behavior analysis of these dampers was a key aspect of the study. The results indicate that combined dampers, especially under cyclic loading, outperform single dampers (Silwal et al., 2016). This improved performance is particularly evident under severe and repeated earthquake loads. The study also revealed that BRB dampers exhibit nonlinear behavior, which should be considered in structural design and analysis (Moradi & Tavakoli, 2019). This nonlinear behavior may lead to variations in structural response under dynamic loads, highlighting the need for advanced analytical models. Specifically, there is a need for the development of numerical and analytical models capable of accurately simulating damper behavior under different loading conditions.

Another important finding is the challenges associated with the design and application of combined BRB and friction dampers. One major challenge is the lack of standardized design guidelines, which currently causes uncertainty for engineers in selecting and designing dampers, potentially affecting overall structural performance (Rahimi et al., 2022).

Additionally, the study indicates that cyclic loading-induced fatigue and variations can influence damper performance, which is particularly relevant for large and complex projects, emphasizing the need for further research (Sultana & Youssef, 2018). The interaction between BRB and friction dampers was also found to significantly improve overall structural behavior, particularly under severe dynamic loads, reducing structural damage and enhancing safety. This finding is especially critical for seismic-prone regions.

Overall, the study highlights the importance of applying combined dampers in steel frame design as an effective tool to control dynamic behavior and enhance seismic performance. Further research is essential to achieve optimized and efficient designs. These results can serve as a reliable reference for researchers and structural engineers, support the development of design guidelines and standards, and provide practical solutions to existing challenges.

6. Conclusion

This meta-analytical study investigated the cyclic behavior of steel frames with combined Buckling-Restrained Braces (BRB) and friction dampers. The results show that the use of combined dampers can significantly improve structural performance under dynamic and seismic loads. BRB dampers are particularly effective in dissipating seismic energy and reducing structural displacements, thereby minimizing damage to structural members. Combining BRB and friction dampers further enhances overall structural performance and reduces internal stresses.

However, important challenges remain, including the lack of specific design standards and the complexity of the nonlinear behavior of dampers. These challenges, along with the need for advanced analytical models, underscore the necessity for further research. Additionally, long-term effects and fatigue due to cyclic loading require special attention.

This study provides a credible resource for researchers and engineers, offering insights for the development of new design guidelines and emphasizing the importance of considering cyclic

behavior and combined damper performance in steel frame design. Ultimately, this research can serve as a starting point for future studies aimed at optimizing the design of combined BRB and friction dampers, contributing to innovative earthquake engineering practices and enhanced structural safety.

7. Practical Recommendations for Future Research

1. **Development of design standards:** Establish specific design standards for combined BRB and friction dampers, including evaluation methods, performance criteria, and implementation guidelines.
2. **Further experimental studies:** Conduct laboratory and field experiments to validate numerical simulations and theoretical analyses, identifying real behavior under dynamic and varying conditions.
3. **Advanced modeling:** Develop numerical and analytical models to accurately simulate damper behavior under different loading conditions, including complex interactions and fatigue effects.
4. **Long-term analysis:** Perform long-term studies to assess the performance of dampers and structures over time, identifying weaknesses and material improvement needs.
5. **Design innovation:** Encourage innovative damper and structural designs using new materials and techniques to improve performance and reduce maintenance costs.
6. **Education and awareness:** Organize workshops and training for engineers and designers on combined dampers and modern structural design techniques.
7. **Fatigue studies:** Investigate fatigue effects from cyclic loads on damper and structural performance to develop improved design solutions.
8. **Multi-factor analysis:** Conduct multi-factor analyses to study interactions between different dampers and structural members for better design efficiency.
9. **Analytical software development:** Develop analytical and simulation tools to evaluate damper and structural behavior under dynamic loads.
10. **Comparative studies:** Perform comparative analyses between BRB and other dampers to identify advantages and optimize damper selection for various projects.

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