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Advances in Seismic Performance of Steel Structures Retrofitted with Knee Braces

Jinjie Liu¹, Dan Zhang², Lei Zhang³, Long Zeng⁴

Student, College of Civil Engineering, Hunan City University, Yiyang, China ^{1,4}

Lecturer, College of Civil Engineering, Hunan City University, Yiyang, China ^{2,3}

ABSTRACT: Although steel structures generally exhibit favorable ductility under seismic loading, those constructed in earlier periods-or those that have undergone functional changes-often suffer from inadequate seismic performance due to outdated design standards. Knee braces have emerged as an efficient retrofitting solution, attracting considerable research interest due to their minimal space occupancy, ease of construction, and effectiveness in enhancing structural stiffness and energy dissipation capacity. This study provides a systematic review of the mechanical behavior, implementation methods and working mechanisms, seismic response characteristics, and performance-based seismic design approaches for steel structures retrofitted with knee braces. First, the hysteretic performance, load-bearing capacity, and ductility of knee-braced retrofitting systems are summarized. Second, the underlying mechanisms of various knee brace configurations-including buckling-restrained knee braces, self-centering knee braces, and those incorporating novel dampers-are analyzed. Third, the seismic response characteristics of different knee-braced systems under earthquake excitations are discussed. Fourth, performance-based plastic design methods and other relevant design approaches are reviewed. Finally, the limitations of existing research are identified, and future research directions are proposed.

KEYWORDS: Steel structures, Seismic retrofitting, Knee brace, Mechanical behavior, Research progress.

I. INTRODUCTION

With the continuous advancement of seismic design theories, the retrofitting of existing steel structures has become a critical issue in engineering practice. Research has shown that earthquakes pose a significant threat to braced steel frames, highlighting the urgent need for efficient and cost-effective seismic mitigation strategies [1]. Among various retrofitting techniques, knee braces have attracted considerable attention due to their unique structural configuration, which provides effective support at beam-column joints and significantly enhances the seismic performance of the structure. Compared with conventional concentrically braced or eccentrically braced systems, knee braces offer several advantages, including reduced space occupancy, minimal impact on building functionality, and ease of installation and replacement [2]. In recent years, researchers have developed a variety of innovative knee brace systems based on traditional configurations, including buckling-restrained knee braces, self-centering knee braces, and those integrated with dampers, and have conducted in-depth investigations into their seismic performance. The emergence of these novel systems has elevated knee-brace retrofitting technology from merely enhancing “strength and stiffness” to achieving the high-performance objectives of “damage controllability and post-earthquake reparability.”

This study aims to systematically review and critically assess recent research advances in the seismic performance of steel structures retrofitted with knee braces. The discussion is organized around the following five core themes: (1) the mechanical behavior of steel structures retrofitted with knee braces; (2) the implementation methods and corresponding working mechanisms of knee-brace retrofitting; (3) the seismic response characteristics of knee-braced steel structures; (4) performance-based seismic design methods for knee-braced steel structures; and (5) research prospects and critical commentary. By systematically synthesizing the existing literature, this review seeks to clarify the development trajectory of the field, evaluate the contributions and limitations of current studies, and provide guidance for future theoretical innovation, technological development, and engineering application.

II. MECHANICAL BEHAVIOR OF STEEL STRUCTURES RETROFITTED WITH KNEE BRACES

Research on the mechanical behavior of steel structures retrofitted with knee braces serves as the foundation for understanding their seismic mechanisms and establishing design methodologies. Such research is primarily conducted through experimental testing, numerical simulation, and theoretical analysis, with a focus on hysteretic performance, load-bearing capacity, stiffness, ductility, and failure modes.

2.1 Hysteretic Performance and Energy Dissipation Capacity

The hysteretic behavior of knee-braced systems directly reflects their energy dissipation capacity. Conventional metal knee braces typically exhibit full hysteretic curves under cyclic loading. For instance, a prefabricated multi-stage metal knee brace damper (MKBD) demonstrated full and symmetric hysteretic curves in tests, with its X-shaped damping plates serving as the primary energy-dissipating components, effectively confining plastic hinge formation within the damper while maintaining the elasticity of beam-column joints [3]. In contrast, novel knee braces incorporating shape memory alloys (SMAs) exhibit a distinctive flag-shaped hysteretic curve, indicating superior self-centering capability and effective reduction of residual deformation [4]. However, research has shown that increasing the stiffness of the SMA damper enhances system strength but may slightly reduce its energy dissipation capacity [5].

For hybrid knee-braced systems, such as those combining hysteretic and viscous energy dissipators, adjusting the equivalent self-centering damping ratio can alter the dynamic response of the system. Under near-field ground motions, increasing the proportion of hysteretic damping reduces ductility demand but may lead to amplified acceleration responses [6]. Furthermore, an innovative brace-brake pad friction damper has been evaluated for its energy dissipation capacity in knee-braced frames through both experimental and numerical approaches [7].

2.2 Load-Bearing Capacity and Stiffness

The incorporation of knee braces significantly enhances the lateral stiffness and load-bearing capacity of structures. Research has shown that compared with conventional semi-rigid frames, innovative integrated knee braces can increase the initial lateral stiffness and yield capacity by 184%-242% and 91%-154%, respectively [8]. For retrofitting methods using high-hardness vise connections, the connection strength can reach levels comparable to those achieved with conventional bolted connections [9]. In precast concrete structures, combining unbonded post-tensioned connections with buckling-restrained knee braces (BRKBs) resulted in a 30% increase in initial joint stiffness compared with cast-in-place specimens [10].

Furthermore, the geometric parameters of knee braces significantly influence their performance. For example, increasing the end width and plate thickness can substantially enhance both initial stiffness and peak load-bearing capacity [3]. In external steel frame joints, knee braces effectively redistribute beam flange stresses to the outer side of the brace, improving the stress state in the joint region [11].

2.3 Ductility and Failure Modes

Properly designed knee braces can guide the structure to achieve a favorable yield mechanism, thereby enhancing ductility. Experimental studies have shown that failure in knee-braced retrofitted joints primarily occurs in the replaceable angle steel connections, greatly improving the reparability of steel joints [12]. For buckling-restrained knee braces (BRKBs), the selection of core material thickness is critical; a recommended optimal thickness range is 10-15 mm, within which the stress ratio between the beam and the BRKB falls within a reasonable range [13].

In certain specialized designs, such as truss moment frames equipped with aluminum-core BRKBs, the BRKB acts as a structural fuse, confining all inelastic deformation to itself and thereby protecting the primary structural members [14]. Additionally, a slender buckling-restrained knee brace damper featuring a steel bar core and restraining tubes effectively suppresses undesired instability failure modes by incorporating contraction allowances [1].

III. IMPLEMENTATION METHODS AND WORKING MECHANISMS OF KNEE-BRACE RETROFITTING

As research has progressed, the forms of knee braces have evolved beyond conventional configurations to encompass a variety of implementations, each characterized by distinct performance attributes. These approaches differ in their working mechanisms, applicable scenarios, and performance objectives.

3.1 Buckling-Restrained Knee Braces (BRKBs)

Buckling-restrained knee braces have emerged as a prominent research focus. By designing the knee brace as a buckling-restrained element, the inherent instability of conventional braces under compression is overcome. Studies have shown that knee-braced frames equipped with either steel or NiTi buckling-restrained braces (BRBs) exhibit stable cyclic behavior. Notably, NiTi BRBs not only satisfy inter-story drift targets but also eliminate residual inter-story drift ratios, demonstrating superior seismic resilience [2]. In seismic design, buckling-restrained knee-braced frames utilize relatively short BRKBs as energy-dissipating devices, providing an efficient seismic force-resisting system suitable for both new construction and retrofitting of existing structures [15].

3.2 Self-Centering and Hybrid Systems

To address the issue of post-earthquake residual deformation, self-centering knee brace technologies have been developed. Researchers have proposed a novel resilient knee-braced frame that combines shape memory alloy (SMA) knee braces with replaceable energy-dissipating connections [16]. In this system, the SMA knee braces primarily provide self-centering capability, while the replaceable connections are responsible for energy dissipation. Numerical simulations indicate that this combination significantly reduces the consumption of SMA material and facilitates post-earthquake repair. In addition, a novel self-centering damper applied to knee-braced frames has been validated for its effectiveness in reducing residual deformations [5].

3.3 Dampers and Innovative Knee Brace Configurations

Beyond the aforementioned types, researchers have developed various damper-integrated knee brace systems. For steel structures mimicking traditional Chinese architectural styles, shear-type and rotational friction dampers have been deployed in the knee-brace region. The shear-type damper was found to be more effective in enhancing overall seismic performance [12]. Finite element analyses have been conducted to investigate the application of six novel yielding tubular dampers in knee braces, revealing that modifications to damper geometry can lead to changes in ultimate strength of up to 6% [17]. Furthermore, a two-level yielding knee-braced frame incorporating a deformation-controlled ring damper has been proposed. Under moderate earthquakes, the ring damper serves as the primary energy dissipator; under severe earthquakes, the knee element acts as a secondary fuse, achieving multi-level seismic protection [18]. For seismically damaged reinforced concrete columns, a temporary retrofitting technique combining a steel jacket with a knee brace has been validated as an effective means to enhance strength and ductility [19].

IV. SEISMIC RESPONSE CHARACTERISTICS OF STEEL STRUCTURES RETROFITTED WITH KNEE BRACES

To gain a deeper understanding of the dynamic behavior and seismic performance of steel structures retrofitted with knee braces under realistic earthquake excitations, researchers have conducted extensive shaking table tests and nonlinear time-history analyses. These investigations have revealed the seismic response characteristics of retrofitted systems and validated the effectiveness of their damage control mechanisms.

4.1 Global Structural Response

Through numerical simulations and shaking table tests, researchers have elucidated the response characteristics of knee-braced retrofitted structures under seismic loading. Nonlinear static analysis and incremental dynamic analysis of steel moment-resisting knee-braced frames (MKFs) have shown that this system effectively satisfies inter-story drift limits [20]. For near-fault ground motions, studies have indicated that such excitations impose higher ductility demands on the system [6]. Buckling-restrained knee-braced frames designed using the uniform damage distribution (UDD) optimization framework achieved a 28% reduction in the damage index [21]. Furthermore, earthquake-induced economic loss assessments have demonstrated that MKF buildings designed in accordance with current codes exhibit favorable seismic loss performance, particularly for low- to mid-rise structures [22].

4.2 Joint and Local Response

Knee braces also significantly influence the local response of beam-column joints. Quasi-static tests comparing conventional rigid joints with novel buckling-restrained knee-braced joints revealed that the latter substantially improve ultimate load-bearing capacity and ductility coefficient, while shifting the plastic hinge outward and thereby protecting the joint core region [23]. A circular hollow section (CHS) knee brace system has been employed to rehabilitate earthquake-damaged steel frames, demonstrating its effectiveness in enhancing the seismic performance of damaged structures [24]. In studies investigating the synergistic behavior of semi-rigid steel frames with prefabricated knee braces, three distinct failure modes were identified: brace-joint yielding, brace-dominated instability, and beam buckling at brace connections [8]. Additionally, it was observed that the influence of the floor slab on the hysteretic behavior of buckling-restrained knee-braced joints is more pronounced in the tension phase than in the compression phase [23].

V. PERFORMANCE-BASED SEISMIC DESIGN METHODS FOR STEEL STRUCTURES RETROFITTED WITH KNEE BRACES

Conventional force-based seismic design (FBD) methods rely on elastic analysis and strength verification, indirectly accounting for plastic deformation capacity through strength reduction factors. However, these methods cannot explicitly define structural performance-such as displacement or damage level-under earthquakes of varying intensities. To achieve predefined seismic performance targets in a more direct and transparent manner, the concept of performance-based seismic design (PBSD) has emerged and gradually become mainstream. For knee-braced retrofitted structures, a variety of performance-based design approaches have been developed and applied.

5.1 Performance-Based Plastic Design (PBDP)

Performance-based plastic design is one of the predominant methods for designing knee-braced systems. This approach designs member cross-sections by presetting the structural yield mechanism and target displacement. Studies have employed the PBDP method to design steel moment-resisting knee-braced frames (MKFs), validating its effectiveness in achieving the intended yield mechanism and satisfying inter-story drift limits [20]. A modified PBDP method, incorporating an energy distribution factor, has been successfully applied to design resilient frames equipped with SMA knee braces and energy-dissipating connections [4]. Furthermore, the design of truss moment frames with aluminum-core BRKBs also adopted the PBDP approach, ensuring that the BRKB acts as a structural fuse as intended [14].

5.2 Design Methods Based on Damage and Mechanism Control

To achieve finer control over structural damage, researchers have proposed various improved design methods. The theory of plastic mechanism control (TPMC) ensures the formation of a global yield mechanism through iterative calculations, thereby avoiding undesirable concentration of damage at specific stories [25]. A plastic design method integrating performance and mechanism control (PDPMC) has been proposed; structures designed using this method exhibit superior control over maximum displacement and inter-story drift compared with those designed using conventional TPMC, while also achieving reductions in steel consumption [26]. In addition, a multi-objective optimization method has been developed that achieves significant improvements in lateral stiffness with only marginal increases in cost through optimization of cross-sectional properties [27].

5.3 Design Parameters and Simplified Approaches

Regarding design parameters, it has been recommended that steel moment-resisting knee-braced frames be designed as moderately ductile systems, with corresponding overstrength and ductility factors proposed [28]. A shear coefficient expression quantifying the influence of knee braces on internal forces in beams and columns has been derived, and a strength hierarchy evaluation method has been developed to predict failure modes of retrofitted joints [29]. Research on the synergistic behavior of semi-rigid steel frames with prefabricated knee braces has provided a theoretical basis for design [8]. For steel structures in traditional Chinese architectural styles, design recommendations have been proposed for beam-column joints incorporating knee-brace friction dampers coupled with shape memory alloy rods [12].

VI. RESEARCH PROSPECTS AND CRITICAL REVIEW OF STEEL STRUCTURES RETROFITTED WITH KNEE BRACES

6.1 Limitations of Existing Research

A critical review of the existing literature reveals several limitations in current research:

Lack of Long-Term Performance Studies: Most existing studies focus on the short-term seismic behavior of knee braces, with limited investigation into long-term performance under material aging, fatigue loading, and corrosive environments. Although research has been conducted on high-hardness wise connections, data on the long-term relaxation behavior of such novel connections remain insufficient [9].

Inufficient Attention to Joint Detailing: Although some studies have addressed gusset plate connections, further research is needed on refined finite element modeling and fatigue life assessment of joints under complex loading conditions. For instance, failure modes identified in studies on semi-rigid frames indicate that local stress concentrations at the lateral screw holes of beam flanges require more detailed design considerations [8].

Lack of Life-Cycle Economic Assessment: Although knee braces are widely recognized for their replaceability, life-cycle economic assessments-including post-earthquake repair costs and downtime losses-for different types of knee brace systems remain scarce. While some studies have addressed earthquake-induced economic losses, they have primarily focused on engineering demand parameters [22].

Insufficient Research on Complex Structural Systems: Existing studies have primarily focused on regular frames, with limited investigation into the application and design methods of knee braces in irregular structures, structures with overhangs, or composite systems. For example, studies on inclined columns have been limited to specific angles and bracing dimensions [30].

6.2 Future Research Directions

In view of the limitations identified above, future research may focus on the following areas:

Further Development of Smart Material-Based Knee Brace Systems: Further exploration is needed to optimize the self-centering and energy dissipation mechanisms of smart materials such as SMAs in knee brace applications, reduce costs, and facilitate practical implementation. For instance, the performance variation of SMA knee-braced frames under different temperature conditions requires further quantification [31].

Resilience-Based Design Methodologies: A structural resilience design framework aimed at post-earthquake functional recovery should be established, incorporating parameters such as residual deformation and repair time into design considerations. Hybrid systems combining SMA knee braces with replaceable energy-dissipating connections offer a promising pathway for achieving resilient design [16].

Structural Health Monitoring and Intelligent Maintenance: Integrating modern sensing technologies, knee brace systems with self-sensing capabilities should be developed to enable real-time monitoring of structural damage states. Preliminary studies exploring the use of plastic heat generation in steel knee braces for damage assessment provide a foundation for future intelligent monitoring approaches [32].

Refined Numerical Simulation and Multi-Scale Analysis: Refined numerical simulations that account for material damage and fracture, connection nonlinearity, and soil-structure interaction should be conducted to elucidate structural failure mechanisms under extreme loading conditions. For example, the influence of core thickness on the failure modes of buckling-restrained knee-braced joints warrants more in-depth finite element analysis [13].

VII. CONCLUSION

Knee-brace retrofitting technology represents an efficient seismic strengthening approach for steel structures. By introducing bracing members at beam-column joints, this technique significantly enhances lateral stiffness, load-bearing capacity, and energy dissipation capacity. Research has shown that from conventional metal knee braces to advanced buckling-restrained knee braces, self-centering knee braces, and damper-integrated systems, this technology has continuously evolved, achieving a performance leap from simple strength enhancement to damage controllability.

and functional recoverability. Notably, the application of buckling-restrained knee braces and self-centering knee braces effectively addresses the inherent shortcomings of conventional braces-namely, compressive buckling and substantial post-earthquake residual deformation-thereby markedly improving the seismic resilience of structures.

In terms of seismic response, knee-braced retrofitted systems effectively control inter-story drift, optimize damage distribution, and guide the structure toward a favorable yield mechanism, thereby protecting the integrity of the primary structural members. Furthermore, the application of advanced design methods-such as performance-based plastic design and damage control design-provides robust tools for the rational design of knee-braced retrofitted structures.

Although current research still exhibits limitations in areas such as long-term performance, joint detailing, economic assessment, and application to complex structural systems, ongoing advancements in smart materials, structural health monitoring technologies, and refined numerical simulations are expected to further enhance the efficacy of knee-brace retrofitting. This technology is poised to play an increasingly critical role in future seismic retrofitting projects, providing a solid foundation for improving the seismic resilience of existing buildings.

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