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Impact of beam–column connection systems on structural integrity of steel structures

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Abstract

Beam–column connections are fundamental components that significantly influence the structural integrity, stability, and load transfer mechanisms in steel structures. This review paper presents a comprehensive assessment of various beam–column connection systems, focusing on bolted, welded, and riveted configurations used with steel and composite columns. The study critically examines existing literature related to the behavior, design approaches, and performance characteristics of these connection types under different loading conditions. The review highlights key aspects such as stress distribution, deformation patterns, ductility, stiffness, and failure modes associated with each connection system. Emphasis is placed on findings obtained through experimental investigations, analytical methods, and finite element modeling techniques, including the application of advanced simulation tools such as ANSYS. Additionally, the influence of connection detailing, material properties, and construction practices on overall structural performance is discussed. The paper also compiles various design recommendations and mitigation strategies proposed by researchers to enhance connection performance and reliability.

Keywords: Beam–column connections; Steel structures; Bolted connections; Welded connections; Riveted connections.

1. Introduction

Steel structures have become an integral part of modern construction owing to their high strength-to-weight ratio, durability, ease of fabrication, and ability to facilitate faster project execution. The performance and reliability of these structures largely depend on the effectiveness of their connections, particularly beam–column joints, which serve as critical load-transfer mechanisms within the structural system. The behaviour of a steel frame under service and extreme loading conditions is strongly influenced by the strength, stiffness, and detailing of these connections, making them an important aspect of structural design and assessment [5], [9].

Beam–column connections are required to transfer axial loads, shear forces, and bending moments between structural members while maintaining overall structural stability. Based on their rotational stiffness and moment-resisting capacity, these connections are generally categorized as rigid, semi-rigid, or flexible. The selected connection system significantly influences the global response of a structure, including lateral displacement, drift characteristics, load redistribution, and energy dissipation during dynamic events such as earthquakes and strong wind actions. Recent studies have highlighted the importance of connection behaviour in determining the seismic performance and resilience of steel framing systems, particularly in regions subjected to high lateral loads [9], [15], [18], [20].

Considerable research has been undertaken over the past few decades to investigate the mechanical performance, failure mechanisms, and design requirements of different beam–column connection systems. Advancements in

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analytical methods, experimental testing, and numerical modelling have provided valuable insights into connection behaviour under static, cyclic, and fire-loading conditions. Despite these developments, the wide variety of connection configurations and design approaches has created a need for a comprehensive evaluation of existing findings. A systematic review of available connection systems is therefore essential for understanding their influence on structural integrity and for identifying areas requiring further investigation [5], [9], [14], [17].

Among the various connection systems used in steel construction, bolted, welded, and riveted connections remain the most common. Each type exhibits distinct structural characteristics and performance attributes. Bolted connections are widely preferred because of their ease of installation, inspectability, and suitability for field erection; however, they may be susceptible to slip, bolt relaxation, bearing deformation, and corrosion-related deterioration over time [1], [2], [4]. Welded connections provide greater continuity and stiffness and are capable of developing high moment resistance, but their performance can be affected by residual stresses, heat-affected zone degradation, and welding imperfections such as porosity, incomplete penetration, and lack of fusion [6], [7], [8]. Riveted connections, although largely replaced by modern fastening techniques, continue to exist in many older industrial and heritage structures. The long-term behaviour of such connections is often influenced by fatigue, material deterioration, and age-related degradation, which may adversely affect structural safety and serviceability if not properly monitored and maintained [1], [2], [3].

1.1. Classification of Beam–Column Connections

Beam–column connections may be classified according to their method of fabrication and the manner in which they transfer forces between structural members. The selection of a suitable connection system depends on factors such as load requirements, construction methodology, structural performance, and maintenance considerations. The three most commonly encountered connection systems in steel structures are bolted, welded, and riveted connections, each possessing distinct behavioural characteristics and engineering applications [5], [9]

1.1.1. Bolted Connections

Bolted connections are among the most widely adopted connection systems in modern steel construction because of their ease of fabrication, rapid installation, and suitability for prefabricated structural components. These connections facilitate convenient inspection, replacement, and maintenance throughout the service life of a structure. Depending on the load-transfer mechanism, bolted joints are generally classified as bearing-type connections and friction-type or high-strength friction grip (HSFG) connections. Bearing-type connections transfer loads through direct contact between the bolt shank and the surrounding plate, whereas friction-type connections rely on clamping force and friction developed between connected surfaces. Although bolted connections offer significant practical advantages, their performance may be influenced by slip, bolt loosening, corrosion, and bearing deformation under repeated or dynamic loading conditions, which can affect stiffness and load-transfer efficiency [1], [2], [4], [9]:

1.1.2. Welded Connections

Welded connections provide a continuous load path between connected members and are extensively used in steel moment-resisting frames where high rigidity and strength are required. The absence of bolt holes results in a more uniform stress distribution and improved structural continuity. Welded joints are capable of transferring substantial axial forces, shear forces, and bending moments, making them suitable for heavily loaded structures. However, the welding process introduces residual stresses and localized metallurgical changes within the heat-affected zone, which may influence long-term structural performance. In addition, welding defects such as porosity, incomplete penetration, slag inclusions, and lack of fusion can reduce connection reliability if appropriate quality control measures are not implemented. Consequently, inspection and non-destructive testing play an important role in ensuring the integrity of welded steel connections [6], [7], [8], [18].

1.1.3. Riveted Connections

Riveted connections were extensively employed in steel construction before the widespread adoption of bolted and welded joints. Although their use in new construction has become uncommon, riveted connections remain prevalent in many existing industrial facilities, railway bridges, and heritage structures. These connections generally exhibit satisfactory ductility and load redistribution capability, which contribute to their durability under service conditions. However, the installation process is labour-intensive and requires specialized workmanship, making it less economical than modern connection techniques. Furthermore, long-term exposure to cyclic loading, environmental effects, and material aging can lead to fatigue-related deterioration and reduction in connection performance. As a result, the evaluation, monitoring, and rehabilitation of riveted connections continue to be important aspects of structural assessment and conservation projects [1], [3], [5]

2. State of Development

Structural behaviour of beam–column connections subjected to static, cyclic, seismic, and dynamic loading conditions. These investigations have provided valuable insights into the load-carrying mechanisms, stiffness characteristics, deformation patterns, and failure modes associated with different connection systems. Experimental findings indicate that the performance of a connection is strongly influenced by factors such as connection detailing, material properties, fabrication quality, and loading history [4], [5], [9].

Research on bolted beam–column connections has demonstrated that bolt pretension, bolt arrangement, and the type of load-transfer mechanism significantly influence connection stiffness and strength. High-strength friction grip connections generally exhibit superior slip resistance and improved load-transfer efficiency compared with conventional bearing-type connections. However, inadequate bolt pretension or long-term deterioration due to corrosion may reduce connection performance and lead to premature deformation under service loads [1], [2], [4]. Experimental investigations on welded connections have shown that these joints typically provide greater rigidity and moment resistance because of their continuous load path. Nevertheless, the presence of residual stresses, welding defects, and stress concentrations within the heat-affected zone can contribute to brittle fracture under severe loading conditions if proper design and quality control measures are not adopted [6], [7], [8].

Studies involving riveted connections have reported satisfactory ductility and stable behaviour under repeated and cyclic loading. The inherent ability of riveted joints to undergo controlled deformation before failure makes them particularly suitable for structures where energy dissipation and load redistribution are important considerations. Consequently, many existing riveted steel structures have demonstrated acceptable performance during seismic and fatigue loading events despite their age [1], [3]. Furthermore, experimental investigations on composite and hybrid connection systems have emphasized the role of interface interaction, confinement effects, and effective force transfer between different materials in improving overall connection behaviour. Enhanced bonding characteristics and proper detailing at the interface have been found to increase stiffness, strength, and deformation capacity, thereby contributing to improved structural integrity and service performance [12], [13], [18].

Table 1 Literature review

Sr. No.	Author(s)	Year	Key Findings
1	K.V. Satheesh Kumar et al.	2021	Examined the behaviour of riveted and bolted joints through analytical calculations, experimental testing, and finite element modelling. The investigation indicated that an increase in plate thickness contributed to higher joint efficiency. The study also observed that riveted joints exhibited comparatively better endurance characteristics than bolted joints for varying pitch distances, highlighting the influence of connection geometry on structural performance [1].
2	Jay Kumar Shah et al.	2025	Investigated the effects of corrosion on bolted steel plate joints using guided-wave ultrasonic inspection techniques. A dispersion index was developed to quantify the level of deterioration and correlate it with structural damage. The findings showed that progressive corrosion reduces load-carrying capacity and modifies the failure mechanism of bolted connections, thereby affecting structural reliability [2].
3	Kuldeep Kaushik et al.	2013	Carried out a comparative assessment of bolted, riveted, and welded beam–column connections using finite element analysis. The study evaluated stress concentration, deformation response, and fatigue behaviour under loading conditions. The results provided a basis for comparing the effectiveness of different connection systems in terms of strength, stiffness, and durability [3].
4	James A. Swanson et al.	2000	Performed experimental investigations on T-stub bolted steel connections to examine their strength and failure behaviour. Different modes of failure, including bolt fracture, plate yielding, and net-section rupture, were identified. The study indicated that existing design formulations generally provide conservative predictions and may not fully represent actual connection behaviour under ultimate loading conditions [4].

5	J. O. Oluwafemi et al.	2020	Presented a review of steel connection systems and their influence on structural response. The study discussed the characteristics of bolted, welded, and riveted connections and emphasized that the selection of a connection type should be based on service requirements, loading conditions, and expected performance throughout the design life of the structure [5].
6	Dariusz Ulbrich et al.	2023	Proposed an ultrasonic surface-wave approach for assessing the quality of spot-welded joints. The research demonstrated that variations in ultrasonic signal amplitude could be effectively used to identify weld integrity and detect potential defects. The technique was found to be suitable for non-destructive evaluation of welded connections [6].
7	Mirjana Opacic et al.	2022	Investigated the application of advanced non-destructive testing methods for evaluating welded joints in pressure vessels. Using phased-array ultrasonic testing, the study demonstrated improved accuracy in defect identification and characterization. The results highlighted the effectiveness of advanced inspection techniques in assessing the integrity of welded components [7].
8	Liang Yang et al.	2024	Developed an ultrasonic spiral C-scan methodology for the inspection of stainless-steel resistance spot welds. The proposed technique successfully detected internal discontinuities and evaluated weld quality with a high degree of precision. The reported error margin was approximately 0.1 mm, indicating strong potential for industrial applications [8].
9	Tiago Ribeiro et al.	2022	Conducted a comprehensive review of seismic design practices related to bolted steel connections. The study identified limitations within current design provisions and emphasized the need for performance-based design approaches. It also highlighted the importance of system-level analysis for accurately evaluating seismic behaviour of steel structures [9].
10	Andrey Lipin et al.	2025	Examined the consequences of design and construction deficiencies on the reliability of steel industrial buildings through finite element simulations. The study found that factors such as connection eccentricity, detailing errors, and fabrication inaccuracies can significantly reduce structural capacity and adversely affect overall safety [10].
11	Honghao Ren et al.	2024	Presented a review of connection systems used in cross-laminated timber structures with emphasis on structural behaviour, rolling shear performance, and sustainability considerations. The study identified several areas requiring further investigation, particularly in relation to design procedures and standardized testing methods for connection evaluation [11].
12	Mohamed Eldeib et al.	2025	Reviewed the structural performance of steel–timber composite systems and discussed the role of connection mechanisms in governing overall behaviour. The study reported that appropriate connection design can enhance stiffness, strength, and fire resistance, while the type of connection remains a key factor influencing composite structural performance [12].

Fei Liao, Xianzhong Li, Wei Wang, Yijia Chen and Guoqiang Li (2022) investigated the seismic performance of Q460 high-strength steel welded cruciform beam–column connections subjected to cyclic loading. The study examined the influence of weld access-hole geometry and local beam flange strengthening on connection behaviour. The experimental results indicated that improved detailing enhanced ductility and delayed crack initiation in the weld region. The strengthened specimens developed stable hysteretic behaviour and improved energy dissipation capacity throughout the loading cycles. Plastic hinges formed away from the column face, thereby reducing stress concentration and improving structural reliability. The connections retained adequate strength even under significant cyclic deformations. The study concluded that optimized welding details and flange reinforcement can improve the seismic performance and structural integrity of steel beam–column joints [15].

Xiang Qiang, Yucheng Shu and Xiaojun Jiang (2022) investigated the behaviour of high-strength steel flange-welded web-bolted beam–column connections under fire exposure conditions. Experimental testing and numerical simulations were performed to evaluate the influence of elevated temperature on connection performance. The results showed a progressive reduction in stiffness, strength, and rotational capacity with increasing temperature. Welded flange regions were found to be more susceptible to thermal stresses, whereas bolted web regions experienced gradual deformation. The numerical model accurately represented the observed response during heating. The study highlighted the importance of considering temperature-dependent material properties in the design of beam–column connections exposed to fire conditions [16].

Bin Lin, Yanyan Wang and Yiyi Chen (2022) carried out a finite element investigation on extended end-plate beam–column connections fabricated from high-strength steel. The study focused on the effects of end-plate thickness, bolt arrangement, and preload conditions on cyclic performance. The findings revealed that thicker end plates reduced prying action and improved rotational stiffness. Stress concentration around bolt holes and welded regions was identified as a critical factor governing failure. The developed numerical model showed good agreement with experimental observations and successfully predicted the failure mechanisms. The authors reported that appropriate end-plate detailing can significantly enhance both strength and ductility of steel moment connections [17].

Shijun Nie, Jun Li, Haibo Wang, Yuting Deng, Zhihua Chen, Mohamed Elchalakani and Ming Liu (2023) investigated the seismic behaviour of welded high-performance steel beam–column joints with various reinforcement configurations. Cyclic loading tests showed that reinforced specimens exhibited higher initial stiffness and improved moment resistance compared with conventional connections. The reinforcement details effectively controlled local buckling and reduced stress concentration near critical weld zones. Stable hysteresis loops and enhanced energy dissipation characteristics were observed throughout the testing programme. The study demonstrated that strengthened connection configurations can substantially improve structural resilience during seismic events [18].

Feng Hu and Zheng Wang (2023) examined the cyclic behaviour of dual-steel beam–column welded flange-bolted web connections. Different steel grades were utilized within the connection region to achieve a balance between strength and ductility. Experimental results indicated stable hysteretic behaviour and considerable deformation capacity prior to failure. The welded flanges primarily resisted bending moments, while the bolted web efficiently transferred shear forces. Damage remained concentrated within predefined yielding regions, preventing premature failure of critical components. The study suggested that dual-steel connection systems can provide improved seismic performance and material efficiency [19].

Feng Hu and Zheng Wang (2024) investigated Q690 high-strength steel welded flange-bolted web beam–column moment connections subjected to cyclic loading. The study evaluated the influence of weld quality and panel-zone strength on overall joint behaviour. Results indicated that improved welding details enhanced ductility and delayed crack formation in critical regions. The panel zone played a significant role in controlling connection deformation and energy dissipation. Connections with balanced panel-zone strength demonstrated superior seismic performance and stable load resistance. The authors emphasized the importance of balanced connection design for achieving reliable structural behaviour [20].

Xiaodong Wei, Leroy Gardner and Ou Zhao (2024) conducted an experimental and numerical investigation on welded stainless-steel beam–column connections under cyclic loading. The objective was to assess the suitability of stainless-steel connections for seismic applications. Experimental observations demonstrated excellent ductility and substantial energy dissipation capacity. Local buckling and weld-region behaviour governed the ultimate failure mode of the specimens. Finite element simulations closely matched the experimental response and accurately predicted stress distribution patterns. The study highlighted the advantages of stainless steel, particularly its durability and corrosion resistance, for demanding structural applications [21].

Shuang Feng, Yong Zhang and Jun Li (2024) investigated the hysteretic performance of reduced beam section (RBS) beam–column moment connections under cyclic loading. The study demonstrated that RBS detailing successfully shifted plastic hinge formation away from the column face. This behaviour reduced the likelihood of brittle fracture occurring within welded connection regions. The specimens exhibited stable hysteretic behaviour and significant energy dissipation throughout testing. Various RBS geometries were assessed to determine their influence on connection performance. The findings confirmed that appropriate beam reduction can improve ductility while maintaining adequate strength [22].

Eduardo Nuñez, Ricardo Torres and Roberto Herrera (2020) examined the cyclic behaviour of hollow structural section beam–column moment connections. The study evaluated the influence of connection geometry and weld detailing on structural performance. Experimental results indicated that local deformation and buckling near the joint region significantly influenced connection response. Despite these effects, the connections maintained satisfactory moment resistance and energy dissipation capacity. Proper weld detailing contributed to improved ductility and delayed failure. The study provided useful insights into the behaviour of hollow-section steel joints under cyclic loading conditions [23].

Yan Sun, Yanyan Wang and Yiyi Chen (2019) investigated the hysteretic behaviour of high-strength steel end-plate beam–column connections subjected to cyclic loading. The study focused on the influence of end-plate thickness, bolt arrangement, and prying action on connection performance. The results showed that properly designed end-plate connections developed excellent moment resistance and rotational capacity. Cyclic degradation was primarily associated with local plate deformation and redistribution of bolt forces. A simplified analytical model was proposed and validated using experimental data, demonstrating its ability to predict cyclic response accurately [24].

Bin Lin, Yanyan Wang and Yiyi Chen (2022) compared the tensile behaviour of conventional and high-strength steel welded-plate preloaded T-stubs. The investigation examined stiffness characteristics, load-transfer mechanisms, and failure modes. The results indicated that high-strength steel T-stubs provided greater load-carrying capacity, while bolt preload improved initial stiffness and reduced slip behaviour. The study contributed to a better understanding of component-level behaviour that influences the performance of bolted beam–column connections [25].

Feng Hu, Zheng Wang and Yong Li (2023) investigated the hysteretic energy dissipation capacity of dual-steel welded-plate preloaded bolted T-stubs under cyclic loading. The study demonstrated stable hysteretic behaviour and effective energy absorption throughout the loading programme. The use of different steel grades improved both strength and ductility while maintaining satisfactory cyclic performance. The findings highlighted the significance of T-stub behaviour in governing the response of bolted steel connection systems [26].

Sheng Jiang, Guoqiang Shi and Ning Zhang (2023) studied cover-plate reinforced beam–column connections between steel beams and high-strength steel box columns. Experimental investigations showed that cover plates increased joint stiffness, moment resistance, and energy dissipation capacity. The reinforcement shifted plastic deformation away from the column face and effectively controlled local buckling. The specimens maintained stable performance throughout cyclic loading. The study recommended cover-plate reinforcement as an effective method for enhancing the seismic resistance of steel structures [27].

Jian Chen and Jun Xue (2025) investigated the shear behaviour and balanced design requirements of panel zones in beam-to-T-shaped steel column joints. The study examined the influence of panel-zone strength on overall connection behaviour. The results showed that weak panel zones experienced excessive shear deformation, while overly rigid panel zones transferred higher stresses to adjacent structural components. A balanced panel-zone design was found to improve ductility, energy dissipation, and overall structural performance. The authors emphasized the importance of panel-zone design in ensuring the integrity and seismic resistance of steel frame connections [28]

3. Behavior of Beam Column Connections

The behaviour of beam–column connections has a significant influence on the overall response of steel structures, as these joints serve as the primary load-transfer mechanism between beams and columns. The structural performance of a connection is governed by several factors, including material properties, connection geometry, fabrication quality, detailing practices, and the type of loading applied. Although structural analysis often assumes idealized rigid or pinned behaviour, practical beam–column connections generally exhibit semi-rigid characteristics that affect stiffness, deformation patterns, and force redistribution within the structural system [5], [9], [17], [24].

Beam–column connections are responsible for transmitting axial forces, shear forces, and bending moments between adjoining members. In bolted connections, force transfer occurs through bearing action between the bolt and connected plate as well as frictional resistance in high-strength friction grip connections. Welded connections provide a continuous load path through material fusion, resulting in efficient stress transmission and enhanced rigidity. Riveted connections exhibit behaviour similar to bearing-type bolted joints; however, they generally offer greater ductility because of their installation method and load-transfer mechanism [1], [3], [4], [5].

A key parameter used to evaluate connection behaviour is the moment–rotation relationship, which defines the rotational response of a connection under applied bending moments. This relationship forms the basis for categorizing connections as rigid, semi-rigid, or flexible. In practical applications, most beam–column connections do not behave as perfectly rigid or perfectly pinned systems. Instead, they possess partial rotational restraint and moment resistance, leading to semi-rigid behaviour. Such behaviour influences frame action, internal force distribution, lateral stiffness, and overall structural displacement under loading conditions [9], [17], [19], [24].

Connection stiffness is another important factor affecting structural performance and is generally represented by initial stiffness, secant stiffness, and tangent stiffness at different stages of loading. Connections with greater stiffness can reduce structural deflections and improve resistance against lateral loads. However, excessively stiff connections may attract higher internal forces, increasing stress concentration in critical regions. Consequently, connection design often aims to achieve an appropriate balance between stiffness, strength, and ductility to ensure satisfactory structural behaviour and energy dissipation capacity [15], [18], [20], [22].

Stress distribution within beam–column connections is typically non-uniform because of geometric discontinuities such as bolt holes, weld profiles, and sudden changes in member cross-sections. In bolted connections, stress concentrations frequently develop around bolt holes where bearing and shear stresses are dominant. Welded joints generally provide a more uniform stress path, although high stress concentrations may occur at weld toes and weld roots, making these locations susceptible to crack initiation and propagation. Riveted connections tend to exhibit a more gradual stress distribution; however, their long-term performance may be influenced by fatigue damage, corrosion, and material degradation. Understanding these stress patterns is essential for improving connection reliability and ensuring long-term structural integrity [2], [6], [7], [8], [10].

3.1. Comparative Evaluation of Analytical and Numerical Results

A reinforced concrete (R.C.C.) short column having a cross-section of 150 mm × 150 mm and a height of 600 mm was considered for the study. The column was reinforced with four 12 mm diameter HYSD Fe500 longitudinal bars and 8 mm diameter lateral ties. The objective was to examine the structural response through analytical calculations and compare it with numerical results obtained from finite element modeling.

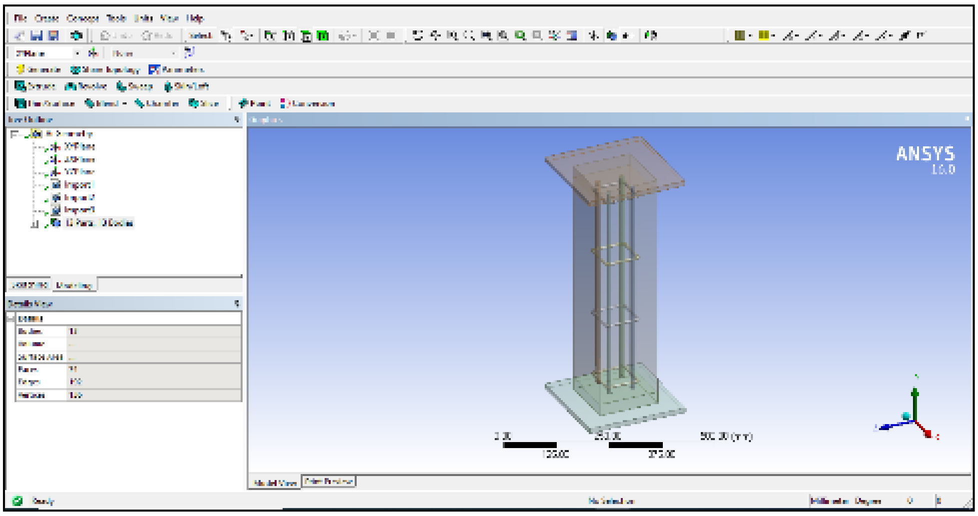

Figure 1 ANSYS Model

Table 2 Analytical Results

Name		Units
Force (V)	6.83E+05	N
Distance	75	mm
Moment (M)	51225000	N·m
Breadth(b)	150	mm
Width(d)	150	mm
Area(A)	22500	mm2
I	42187500	mm4
Z	562500	mm3

y	75	
E		
length mm	600	
shear stress (r)= V / A	182.1333333	N/mm2
Normal Stress (σ)= V / A + M / Z	30.35555556	N/mm2
Equivalent Stress = SQRT(σ^2 +3r^2)	91.06666667	N/mm2
Total Deformation mm = (V×L)/(A× E)	12	mm

Table 3 Comparison of Total Deformation

Method	**Total Deformation (mm)**
Analytical	12
ANSYS	13.2

4. Discussion

The comparison highlights that the numerical model predicts slightly higher deformation than the analytical method. This difference can be attributed to the ability of finite element modeling to capture stress concentration, boundary effects, and material nonlinearity more accurately. The close correlation between the two results indicates that the analytical approach provides a reasonable estimation of structural behavior, while numerical analysis offers enhanced precision.

5. Conclusion

5.1. Findings from Literature Review

The literature indicates that the structural integrity and overall performance of steel structures are predominantly governed by the behavior of their connections rather than by individual structural members. Previous studies on bolted, welded, and riveted connections reveal that each connection type exhibits distinct characteristics in terms of stiffness, strength, load transfer mechanism, and deformation behavior. Bolted connections are generally associated with issues such as slip, bearing deformation, and reduction in stiffness under repeated or dynamic loading. Welded connections, while providing higher rigidity, are sensitive to stress concentration, residual stresses, and potential cracking, which may adversely affect long-term performance. Riveted connections, though known for their ductile behavior and redundancy, tend to exhibit reduced efficiency due to aging effects and corrosion-related deterioration

5.2. Gap Identification

From the literature review, it is observed that most existing studies focus on individual steel connection types rather than providing a comparative analytical evaluation of bolted, welded, and riveted connections under identical geometric and loading conditions. Limited research is available that systematically compares these connection types using standardized I-section configurations and uniform design parameters within a single analytical framework. Furthermore, although advanced software tools such as ANSYS Structures are extensively used for connection modeling, discrepancies in connection behavior prediction due to modeling idealizations and simplified assumptions remain insufficiently addressed

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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