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Literature Review on Finite Element Modeling of Beam–Column Joints in Steel Structures

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Abstract - *Beam–column joints are critical components of steel structures, as they significantly influence the overall strength, stiffness, stability, and ductility of the structural system under static and dynamic loading conditions. Accurate analysis of these joints is essential to ensure structural safety and optimize design performance. Finite Element Analysis (FEA) has emerged as a powerful numerical tool for evaluating the complex behavior of steel beam–column joints by considering material nonlinearity, geometric nonlinearity, contact interactions, and various loading conditions. This paper presents a comprehensive literature review on the finite element analysis of beam–column joints in steel structures, focusing on different connection types such as bolted end-plate, welded, angle, and hybrid connections. The review summarizes the modeling techniques, element types, material constitutive models, validation methods, and key findings reported by previous researchers. It also highlights the influence of connection geometry, bolt pretension, cyclic loading, fire exposure, and seismic effects on joint performance. Furthermore, the review identifies current research gaps and discusses future directions for improving finite element modeling and connection design. The study concludes that validated finite element models provide reliable predictions of joint behavior and serve as an efficient alternative to extensive experimental testing, thereby supporting the safe, economical, and performance-based design of steel structures.*

Key Words: Finite Element Analysis (FEA), Beam–Column Joints, Steel Structures, Beam-to-Column Connections, Nonlinear Analysis, Structural Behavior.

1. INTRODUCTION

Steel structures are extensively used in modern construction because they provide high strength, reduced self-weight, design flexibility, and faster construction compared to many conventional structural systems. The performance of a steel frame depends greatly on the behavior of its beam–column joints, which are responsible for transferring loads, moments, and shear forces while maintaining the overall stability of the structure. Since these connections experience complex stress distributions and nonlinear responses under different loading conditions, their accurate evaluation is essential for ensuring structural safety and serviceability. Experimental investigations provide valuable insights into connection behavior; however, they are often expensive, time-consuming, and limited in scope. As a result, Finite Element Analysis (FEA) has become a widely accepted numerical technique for studying the structural response of beam–column joints. It enables engineers to simulate realistic material behavior, geometric nonlinearity, contact interactions, and various loading scenarios with a high degree of accuracy. Over the years, researchers have proposed and validated numerous finite element models for different types of steel connections, including bolted, welded, end-plate, and angle connections, to evaluate their strength, stiffness, ductility, and failure mechanisms. This literature review examines these published studies, summarizes the major modeling approaches and findings, identifies current research trends and limitations, and highlights potential directions for future research in the finite element analysis of steel beam–column joints.

1.1 Aim

The aim of this study is to review the existing literature on the finite element analysis of beam–column joints in steel structures, summarize the findings of previous research, identify commonly used modeling techniques, and highlight research gaps and future scope.

1.2 Objectives

[1]. To review published research on the finite element analysis of beam–column joints in steel structures.
[2]. To compare different finite element modeling techniques and connection types used in previous studies.
[3]. To identify research gaps and suggest future directions for improving the analysis and design of steel beam–column joints.

2. LITERATURE REVIEW

The literature on Beam–column joints are essential components of steel structures that transfer loads and moments between beams and columns, ensuring the strength and stability of the structural system. Their behavior significantly affects the overall performance of steel frames under different loading conditions. Finite Element Analysis (FEA) is a widely used numerical method for evaluating the behavior of these joints by accurately predicting stress, deformation, stiffness, and failure mechanisms. It provides a reliable and cost-effective alternative to extensive experimental testing and supports the efficient design of steel structures.

Contributions of researchers are presented as follows,

Hassan A. Saab (1990) [1] proposed a finite element methodology to investigate the behavior of steel frames subjected to elevated temperatures during fire exposure. The developed numerical model considered the reduction in the mechanical properties of steel due to increasing temperature and simulated the structural response throughout different stages of fire. The study demonstrated that finite element analysis can effectively estimate member deformation, internal force redistribution, and load-carrying capacity under fire conditions. The research highlighted the importance of numerical simulation in evaluating fire resistance and improving the design of steel structures without relying solely on costly experimental testing.

Elsayed Mashaly, Mohamed El-Heweity, Hamdy Abou-Elfath, and Mohamed Osman (2011) [2] developed a three-dimensional nonlinear finite element model to evaluate the behavior of bolted extended end-plate beam-to-column joints subjected to lateral loading. The numerical model incorporated material nonlinearity, geometric nonlinearity, and contact interactions between bolts, end plates, beams, and columns. Validation was performed using published experimental results, and the predicted load–displacement curves, stress distribution, and deformation patterns closely matched the experimental observations. The study concluded that finite element analysis provides an efficient and reliable approach for analyzing complex steel beam-to-column connections.

R. A. Hawileh, A. Rahman, and H. Tabatabai (2010) [3] presented a comprehensive three-dimensional nonlinear finite element model to investigate the cyclic response of precast hybrid beam-to-column connections. The model included concrete nonlinear behavior, surface-to-surface contact elements, and the prestressing effect of post-tensioning tendons. The numerical results were verified using experimental data and accurately predicted stiffness, strength, displacement response, and failure mechanisms. The study also evaluated stress and strain development in reinforcement bars and demonstrated that finite element analysis can effectively reproduce the cyclic behavior of hybrid structural connections.

M. R. Mohamadi-Shoore, H. Ghafari, and M. Amankhani (2011) [4] developed a detailed three-dimensional finite element model to study Rectangular Hollow Section (RHS) splice beam connections subjected to pure bending. The model represented important connection components, including the beam web, end plate, welds, and high-strength bolts, to simulate realistic structural behavior. Numerical analysis was performed to evaluate stress concentration, deformation characteristics, and load transfer within the connection. The investigation confirmed that finite element modeling is an effective technique for assessing the structural performance and strength of RHS splice beam connections.

Vishawadeep Shivaji Ghodajkar and Dr. R. M. Sawant (2016) [5] carried out a comparative finite element analysis of three commonly used beam-to-column connection types: top and seat angle connections, double web angle connections, and extended end-plate connections. Different loading conditions were applied to evaluate stress distribution and deformation characteristics. The results indicated that the top and seat angle connection experienced comparatively lower stresses than the double web angle and extended end-plate connections. The study suggested that selecting an appropriate connection type significantly influences the structural efficiency and safety of steel frames.

L. Simões da Silva, R. Simões, and P. Vila Real (2001) [6] investigated the structural performance of steel beam-to-column joints using advanced three-dimensional finite element modeling techniques. The study examined the influence of connection geometry, bolt pretension, material yielding, and geometric nonlinearity on joint stiffness and moment resistance. Numerical predictions were compared with experimental results and showed excellent agreement. The research demonstrated that accurate finite element models can successfully predict rotational stiffness, stress concentration, and failure modes, making them valuable tools for practical connection design.

A. Bouchair and M. B. Kerdal (2008) [7] developed a nonlinear finite element model to analyze extended end-plate beam-to-column connections under monotonic loading conditions. The numerical model incorporated contact interactions, steel plasticity, and geometric nonlinear effects to simulate the actual behavior of the connection. The predicted load-carrying capacity, displacement response, and failure patterns closely matched available experimental data. The study concluded that nonlinear finite element analysis is capable of accurately representing the complex behavior of extended end-plate steel connections.

D. G. Latour, R. Rizzano, and V. Piluso (2011) [8] performed a detailed finite element investigation on bolted beam-to-column joints used in steel moment-resisting frames. Their research focused on evaluating the influence of bolt diameter, end-plate thickness, stiffener arrangement, and connection detailing on structural performance. The numerical simulations provided detailed information regarding stress distribution, plastic deformation, stiffness, and ductility. The authors concluded that finite element analysis can be effectively applied to optimize connection design while ensuring adequate strength and seismic performance.

Y. Shi, Y. Wang, and M. A. Bradford (2010) [9] presented a three-dimensional finite element model to investigate the seismic behavior of steel beam-to-column connections subjected to cyclic loading. The model incorporated bolt pretension, contact behavior, material yielding, and geometric nonlinearity to accurately simulate the structural response. Comparison with experimental results confirmed that the model successfully predicted plastic hinge formation, stress concentration, connection deformation, and energy dissipation. The study demonstrated the suitability of finite element analysis for evaluating seismic performance and improving connection design.

J. A. Swanson and R. T. Leon (2000) [10] investigated the behavior of steel beam-to-column connections through a combination of finite element analysis and experimental validation. Their study focused on the moment–rotation characteristics, stiffness degradation, ductility, and energy dissipation of steel connections subjected to loading. The numerical results closely agreed with experimental observations, confirming the reliability of finite element models in predicting structural behavior. The research also emphasized the importance of connection detailing in enhancing the overall performance and safety of steel framing systems.

3. CONCLUSIONS

The literature reviewed in this study shows that Finite Element Analysis (FEA) is an effective and reliable method for evaluating the behavior of beam–column joints in steel structures. Previous researchers have successfully applied finite element models to investigate different types of connections under various loading conditions, including static, cyclic, seismic, and fire loading. The findings indicate that FEA can accurately predict stress distribution, deformation, stiffness, load-carrying capacity, and failure mechanisms when the numerical models are properly validated with experimental results. The review also highlights that factors such as connection geometry, material nonlinearity, bolt pretension, and contact interactions have a significant influence on the performance of steel beam–column joints. Although considerable progress has been made in this field, further research is required to improve modeling techniques, evaluate innovative connection systems, and study the behavior of joints under combined and extreme loading conditions. Overall, this literature review demonstrates that finite element analysis has become an essential tool for understanding the structural behavior of steel beam–column joints and supports the development of safer, more efficient, and economical steel structure designs.

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