Advanced Computing–Based Modeling of Steel Connection Behavior and Stability Performance using ETABS And STAAD Pro

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Abstract

Advanced computational modeling has become an essential tool for evaluating the structural performance of steel frame systems and their connection behavior under complex loading conditions. This study examined the structural behavior and stability performance of steel connections using advanced computing-based modeling through ETABS and STAAD Pro. A quantitative comparative simulation design was adopted to analyze the response of multistory steel frame structures under standardized modeling conditions. A total of 24 three-dimensional steel structural models were developed and analyzed using identical geometric properties, material characteristics, and boundary conditions in both software platforms. The analytical dataset consisted of 960 structural observations derived from multiple load combinations including gravity, wind, and seismic loading scenarios. Key structural performance indicators evaluated in the study included maximum displacement, interstory drift, column axial force, beam shear force, bending moment distribution, and structural stability indices. The findings demonstrated that both ETABS and STAAD Pro produced generally consistent structural response patterns across the simulated models. The average maximum displacement predicted by ETABS was 40.56 mm, compared with 37.12 mm generated by STAAD Pro, indicating slightly greater lateral deformation predicted by ETABS. Similarly, the average interstory drift ratio was 0.0023 in ETABS and 0.0021 in STAAD Pro, confirming similar deformation trends between the two platforms. In contrast, STAAD Pro simulations produced higher internal force values in structural members, with average column axial forces of 1287.66 kN compared with 1218.43 kN in ETABS, and average beam bending moments of 366.88 kN·m compared with 349.72 kN·m in ETABS. Subgroup analysis further showed that structural models with semi-rigid connections produced greater deformation responses, with an average displacement of 42.63 mm compared with 35.18 mm in rigid connection models. Statistical testing confirmed that several structural indicators exhibited significant differences between the two software platforms, although effect size analysis indicated that these differences were generally small to moderate in magnitude. Overall, the results demonstrated that both ETABS and STAAD Pro provide reliable analytical capabilities for modeling steel structural behavior while exhibiting modest numerical variation in certain structural performance indicators.

INTRODUCTION

Advanced computing has become an essential component of modern structural engineering, particularly in the modeling and analysis of steel connection behavior and structural stability. Advanced computing refers to the use of sophisticated computational algorithms, high-performance computing systems, and simulation software to analyze complex engineering problems that cannot be efficiently solved using traditional analytical methods (Ghali et al., 2017). Structural engineering itself is defined as the discipline concerned with the design, analysis, and evaluation of structures capable of safely supporting loads and environmental forces throughout their lifecycle. Steel structures, which are widely used in high-rise buildings, bridges, industrial facilities, and infrastructure projects, rely heavily on the performance of structural connections that transfer loads between structural members. Steel connections are defined as the joining mechanisms between beams, columns, and other steel components that ensure load continuity and structural integrity. The behavior of these connections directly influences the overall stability, safety, and resilience of a structure. The global significance of steel connection modeling has increased due to rapid urbanization, infrastructure development, and the construction of increasingly complex structural systems (Anick & Tasnim, 2022; Siddique & Amin, 2022). Modern buildings often incorporate irregular geometries, high-strength materials, and advanced load-resisting systems, which demand precise computational modeling to evaluate structural performance under diverse loading conditions such as gravity, wind, seismic forces, and thermal stresses.

Traditional hand calculations and simplified design formulas are limited in their ability to capture nonlinear behavior, local buckling, material yielding, and connection flexibility. Consequently, structural engineers increasingly rely on computational tools to simulate realistic structural behavior and to support evidence-based design decisions. Computational structural analysis enables engineers to represent structural systems mathematically using numerical methods such as the finite element method (FEM). FEM divides complex structures into smaller elements whose mechanical responses can be computed and assembled to represent the behavior of the entire system (Buchanan & Gardner, 2019). Through such modeling techniques, engineers can investigate stress distribution, deformation patterns, connection rigidity, and potential failure mechanisms. The integration of advanced computing tools into structural engineering practice has significantly enhanced the ability to design safe and economical steel structures (Md & Islam, 2022; Shahinur & Sultan, 2022). These computational capabilities allow engineers to simulate multiple load scenarios, assess structural redundancy, and identify vulnerabilities before physical construction occurs. Internationally, the reliability of steel structures is directly linked to the accuracy of connection modeling (Jinnat & Rakib, 2023; Mostafa & Tohidul, 2022). Steel connections often represent the most critical and complex components of a structural system because they concentrate stresses and influence load transfer paths. Inadequate modeling of these connections can lead to inaccurate predictions of structural behavior, potentially compromising safety and performance. The advancement of computational modeling software has therefore become a cornerstone of structural engineering research and professional practice. Numerous studies have emphasized the importance of computational analysis in evaluating steel connection performance, particularly for complex building systems and high-load environments (Dimiduk et al., 2018). The development of advanced computing tools has transformed engineering workflows by enabling engineers to visualize structural responses through three-dimensional models and dynamic simulations. These tools integrate structural mechanics principles with numerical algorithms to provide comprehensive analysis environments where engineers can evaluate structural stability, connection performance, and system interactions simultaneously. As a result, advanced computing has become fundamental for both research and professional practice in structural engineering, providing a reliable framework for understanding and predicting the behavior of steel connections in modern infrastructure systems.

Steel connection behavior refers to the mechanical response of joint interfaces between steel structural elements when subjected to external loads. These responses include deformation, rotation, stress redistribution, and potential failure modes that occur within connection components such as bolts, welds, plates, and gusset assemblies. Structural connections serve as the primary load transfer mechanisms within steel frameworks, ensuring that forces are distributed across structural members

in a stable and predictable manner (Ma et al., 2020; Khaled & Mosheur, 2023; Shahab & Aditya, 2023). The classification of steel connections commonly includes rigid connections, semi-rigid connections, and pinned connections, each representing different levels of rotational stiffness and load-transfer capacity. The performance of steel connections is influenced by multiple factors including connection geometry, material properties, fabrication quality, loading conditions, and installation accuracy. In many structural systems, connections are subjected to complex combinations of axial forces, shear forces, bending moments, and torsional stresses (Hasan Or et al., 2023; Mehedi & Nahar, 2023). These interactions produce nonlinear responses that cannot be fully captured through simplified theoretical models. Structural engineers therefore rely on computational modeling to evaluate the behavior of steel connections under realistic conditions, allowing them to examine deformation patterns, stress concentrations, and potential instability mechanisms. Steel connections play a fundamental role in determining the stiffness and stability of structural systems (Sultan & Anick, 2023; Mostafa, 2023). The rigidity or flexibility of a connection affects how loads are distributed between structural members and how the structure responds to external forces. Rigid connections provide significant rotational restraint and contribute to frame stability, while pinned connections allow rotation and primarily transfer shear forces (Khan & Yairi, 2018; Ratul & Aditya, 2023; Tasnim & Zaheda, 2023). Semi-rigid connections exhibit intermediate behavior and are commonly found in practical steel structures. Understanding these behavioral characteristics is essential for accurate structural analysis and design. The complexity of steel connection behavior has been extensively studied in structural engineering literature. Researchers have explored the mechanical properties of bolted and welded connections, the influence of connection detailing on structural performance, and the effects of cyclic loading on joint stability (Zaheda & Farabe, 2023). Experimental investigations have provided valuable insights into connection strength and deformation characteristics, while numerical simulations have enabled the exploration of large-scale structural systems that cannot easily be replicated in laboratory settings. The integration of experimental data with computational models has strengthened the reliability of connection behavior predictions. In large infrastructure projects such as bridges, stadiums, and high-rise buildings, the accurate modeling of steel connections is essential for ensuring structural safety and serviceability. Structural failures in past engineering history have highlighted the critical role of connections in maintaining structural integrity (Helo & Hao, 2019). As a result, international engineering standards and design codes emphasize the importance of connection design and analysis in structural engineering practice. Computational modeling tools provide engineers with the capability to simulate these connections under realistic loading scenarios, improving the accuracy of structural evaluations and supporting safer infrastructure development worldwide.

**Figure 1: Advanced Computing in Structural Engineering**
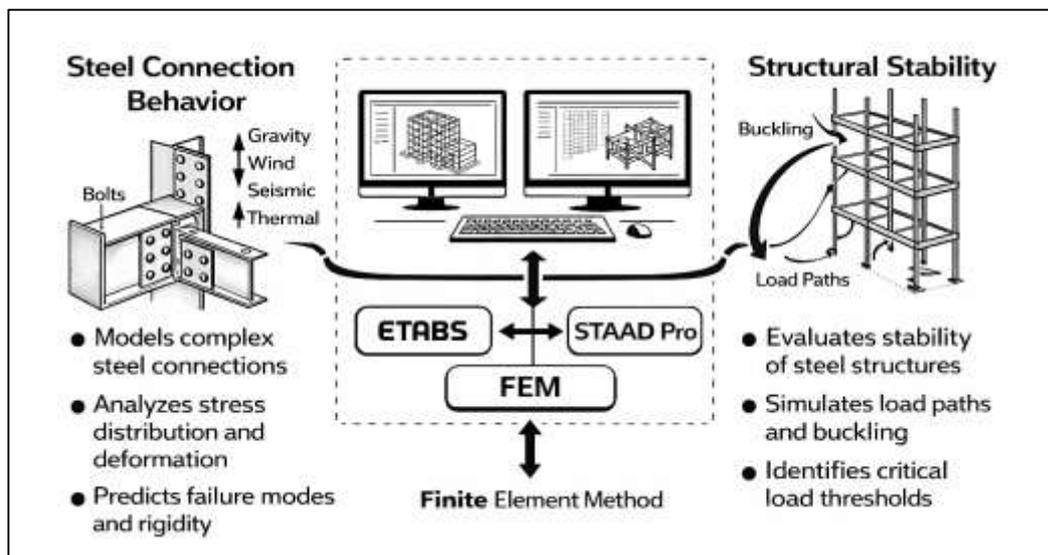
Structural stability refers to the capacity of a structural system to maintain equilibrium and resist collapse when subjected to external loads or disturbances. Stability performance in steel structures involves the ability of beams, columns, and connections to sustain loads without experiencing excessive deformation, buckling, or progressive failure. Stability analysis is therefore a critical aspect of structural engineering, particularly in steel frameworks where slender members and complex load interactions can create conditions for instability (Karthika et al., 2017). Steel structures are widely used due to their high strength-to-weight ratio, ductility, and versatility in architectural design. These properties make steel an attractive material for constructing large-scale infrastructure and high-rise buildings. The stability of such structures depends on multiple factors including member stiffness, connection rigidity, geometric configuration, and load distribution. Structural stability analysis evaluates these factors to determine whether a structure can safely withstand expected loads during its operational lifespan. One of the major challenges in stability analysis is the interaction between structural members and connections. The stiffness characteristics of connections influence how loads are transferred throughout the structure and how structural components respond to deformation. Semi-rigid connections, for example, can alter load paths and affect the overall stability of a structural frame (Eastman, 2018). Accurate representation of these connection behaviors is therefore essential for predicting structural performance under various loading conditions. Structural engineers use computational methods to evaluate different forms of instability, including global buckling, local buckling, and lateral-torsional buckling. These instability phenomena occur when structural elements lose their ability to carry loads due to excessive deformation or stress redistribution. Computational models allow engineers to simulate these behaviors and assess the conditions under which instability may occur. Through such simulations, engineers can identify critical load thresholds and design structures that maintain stability under extreme conditions. International infrastructure development increasingly relies on computational stability analysis to ensure the safety of complex structural systems. Modern architectural designs often incorporate large spans, irregular geometries, and innovative structural configurations that require advanced analysis techniques (Wu & Feng, 2018). Computational modeling software enables engineers to evaluate these designs accurately, providing insights into structural performance that would be difficult to obtain through traditional analytical methods. The ability to model structural stability using advanced computing tools has therefore become essential for modern engineering practice.

Computational modeling in structural engineering involves the representation of physical structures through mathematical models that simulate structural behavior under various conditions. One of the most widely used techniques in this context is finite element analysis (FEA), a numerical method that divides complex structures into smaller elements connected at nodes (J. Wang et al., 2018). Each element represents a portion of the structure with defined material properties and mechanical characteristics, allowing engineers to compute stresses, strains, and displacements throughout the system. Finite element analysis has become a cornerstone of modern structural engineering because it allows for the analysis of complex geometries and nonlinear behaviors that are difficult to address through traditional analytical approaches. Steel structures often involve intricate connection configurations and multiple load interactions that require detailed computational evaluation. FEA enables engineers to capture these complexities by modeling structural components with high levels of precision. The application of finite element methods to steel connection analysis provides valuable insights into stress distribution, deformation patterns, and failure mechanisms (Sharma et al., 2020). By modeling connection components such as bolts, welds, and plates, engineers can evaluate how forces are transmitted between structural members. These models allow for the examination of local stress concentrations and potential points of structural weakness. Such detailed analysis contributes to the optimization of connection designs and the improvement of structural safety. Computational modeling also supports parametric analysis, where engineers evaluate how changes in structural parameters influence overall system performance. Parameters such as connection stiffness, member dimensions, material properties, and loading conditions can be systematically varied within computational models to observe their effects on structural behavior. This capability provides engineers with a powerful tool for exploring design alternatives and identifying optimal structural configurations. The global adoption of computational modeling has significantly enhanced the reliability of structural engineering analysis.

Modern structural engineering software integrates advanced numerical algorithms with user-friendly modeling interfaces, enabling engineers to create detailed structural models and perform sophisticated analyses efficiently (Paoletti, 2017). The integration of computational modeling techniques into engineering practice has therefore played a central role in improving the safety, efficiency, and innovation of modern structural systems.

Figure 2: Advanced Computing for Steel Stability
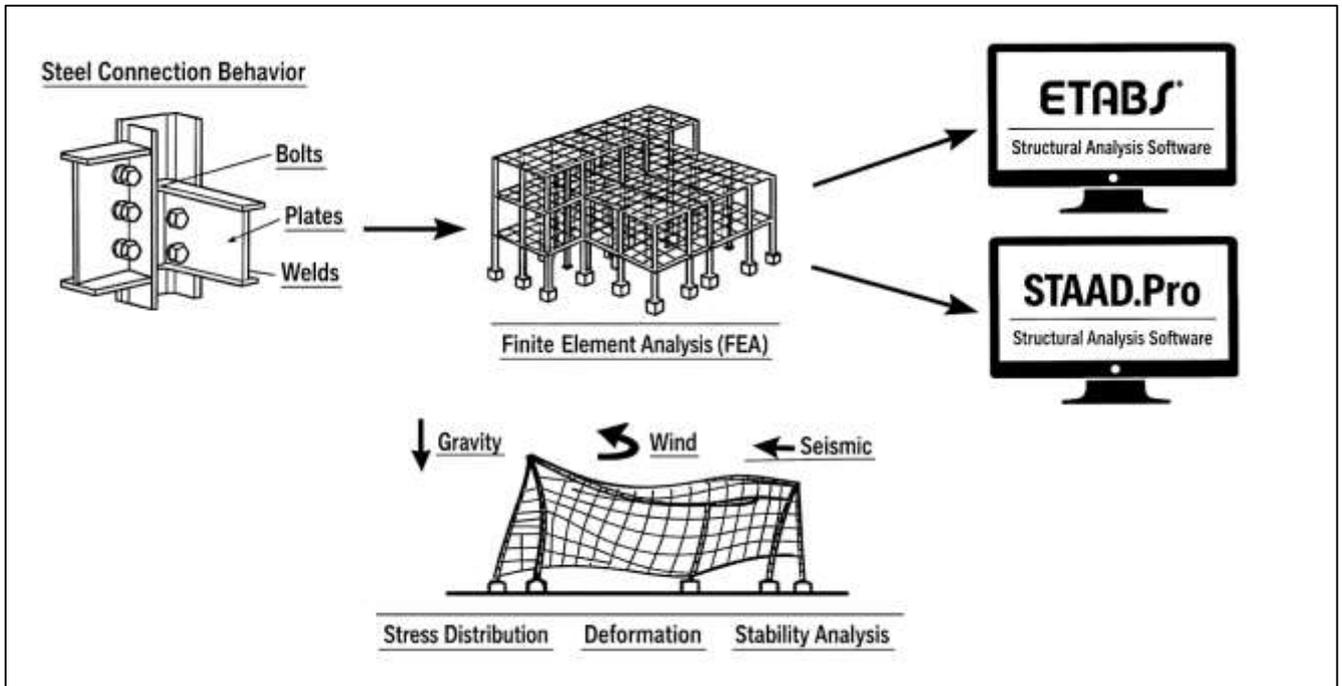
ETABS, which stands for Extended Three-Dimensional Analysis of Building Systems, is a specialized structural engineering software designed for the analysis and design of building structures. The software provides a comprehensive modeling environment that allows engineers to create detailed representations of structural systems, including beams, columns, slabs, and connections. ETABS integrates advanced computational algorithms with graphical modeling tools, enabling engineers to perform complex structural analyses efficiently (Chen, 2017). The primary strength of ETABS lies in its ability to model multi-story buildings and complex structural frameworks. Engineers can define material properties, structural geometry, and loading conditions within the software environment, allowing them to simulate the behavior of entire structural systems. ETABS supports both linear and nonlinear analysis methods, providing engineers with the flexibility to evaluate structural performance under a wide range of conditions. One of the key features of ETABS is its capacity to analyze structural stability and load distribution within building frameworks. The software incorporates finite element modeling techniques that allow engineers to evaluate structural responses to gravity loads, wind loads, seismic forces, and other environmental conditions (Zhu et al., 2018). Through these analyses, engineers can determine stress distribution, displacement patterns, and structural stability characteristics. ETABS also supports advanced visualization tools that enable engineers to observe structural behavior through graphical representations. Deformation diagrams, stress contours, and load path visualizations provide insights into how structural components interact within the overall system. These visual tools help engineers identify critical structural regions that require further investigation or design optimization. The international use of ETABS in structural engineering practice highlights its importance as a computational modeling platform (Ghaffarianhoseini et al., 2017). The software has been widely adopted in both academic research and professional engineering projects, contributing to the design and evaluation of numerous infrastructure systems worldwide. Its ability to integrate structural analysis with design processes has made ETABS an essential tool for engineers working with complex building structures.

STAAD Pro is another widely used structural analysis and design software that supports the modeling of a wide range of structural systems including buildings, bridges, industrial structures, and infrastructure projects. The software provides engineers with a versatile computational environment for performing structural analysis using advanced numerical techniques. STAAD Pro integrates finite element analysis with structural design capabilities, enabling engineers to evaluate structural performance under diverse loading conditions (J. Li et al., 2017). The software allows engineers to create detailed three-dimensional structural models that represent real-world engineering systems. Structural members, materials, boundary conditions, and loads can be defined within the modeling interface, enabling comprehensive analysis of structural behavior. STAAD Pro supports various types of analysis including static analysis, dynamic analysis, stability analysis, and nonlinear analysis. One of the significant advantages of STAAD Pro is its capability to evaluate structural stability and load distribution in complex structural systems. The software incorporates advanced algorithms that simulate the interaction between structural members and connections (Miranda et al., 2021). These simulations allow engineers to investigate stress distribution, deformation patterns, and potential instability mechanisms within steel frameworks. STAAD Pro also provides extensive design modules that enable engineers to evaluate structural elements according to international design standards. Engineers can assess the adequacy of structural members and connections based on strength, stiffness, and serviceability criteria. This capability supports the integration of structural analysis with engineering design processes. The use of STAAD Pro in structural engineering research and practice demonstrates the growing reliance on advanced computational tools for structural evaluation. Engineers across the world utilize the software to analyze infrastructure systems, assess structural safety, and support engineering design decisions (Singh et al., 2019). Its integration of computational modeling and design capabilities makes STAAD Pro an important platform for evaluating steel connection behavior and structural stability.

The integration of advanced computing tools such as ETABS and STAAD Pro has significantly enhanced the ability of engineers to model and analyze steel connection behavior within complex structural systems. These platforms combine sophisticated numerical algorithms with intuitive modeling environments, enabling engineers to create highly detailed representations of structural frameworks (Li et al., 2017). Through these tools, engineers can simulate structural responses under multiple loading conditions and evaluate how connection behavior influences overall structural performance. The use of computational modeling software supports the analysis of large-scale structural systems that would be difficult to evaluate through manual calculations. By incorporating connection stiffness, material properties, and load interactions into computational models, engineers can obtain a more realistic representation of structural behavior. These models provide valuable insights into stress distribution, deformation characteristics, and stability performance. Advanced computing tools also facilitate the comparison of different structural design scenarios. Engineers can modify connection configurations, structural layouts, and material properties within computational models to observe how these changes affect structural performance. This capability supports evidence-based design decisions and allows engineers to optimize structural systems for safety and efficiency. The application of computational modeling to steel connection analysis contributes to the improvement of structural engineering knowledge and practice (Dilberoglu et al., 2017). Through simulation-based analysis, engineers can investigate complex structural phenomena that are difficult to observe experimentally. Computational tools therefore serve as an important bridge between theoretical structural mechanics and practical engineering design. The growing reliance on advanced computing in structural engineering reflects the increasing complexity of modern infrastructure systems. As buildings and structural frameworks become larger and more sophisticated, computational modeling tools provide the analytical capabilities required to ensure structural stability and safety. The integration of ETABS and STAAD Pro within engineering workflows represents an important advancement in the modeling and evaluation of steel connection behavior and structural performance in contemporary structural engineering (Cui & Zhang, 2021).

The primary objective of this quantitative research is to investigate the structural behavior and stability performance of steel connections through advanced computational modeling using ETABS and STAAD Pro. Steel connections represent critical components within structural systems because they

govern the transfer of loads between structural members and influence the global stability of steel frameworks. Accurate analysis of these connections is therefore essential for ensuring structural reliability, safety, and efficient load distribution. This study aims to quantitatively model and evaluate the mechanical response of steel connections under different loading conditions, focusing on stress distribution, deformation characteristics, and stability performance within steel structural systems. By employing advanced structural analysis software, the research seeks to generate detailed numerical models that simulate real-world structural behavior and provide measurable outputs related to connection performance and system stability. Another objective of the study is to assess how computational modeling tools can effectively represent the interaction between steel members and their connections within complex structural frameworks. ETABS and STAAD Pro offer advanced numerical analysis capabilities that allow engineers to construct three-dimensional structural models, apply multiple load cases, and evaluate the resulting structural responses. Through the application of these tools, the research aims to analyze the influence of connection configurations, stiffness characteristics, and load distribution on the overall performance of steel structures. The study will focus on identifying how variations in connection properties affect structural displacement, internal force distribution, and stability parameters within simulated structural models. The research also intends to quantitatively compare the modeling outputs generated by ETABS and STAAD Pro in the evaluation of steel connection behavior. By applying identical structural configurations and loading conditions within both computational environments, the study aims to examine the consistency, analytical capabilities, and performance outcomes of these two widely used structural engineering platforms. This comparison will provide measurable insights into the effectiveness of advanced computing-based modeling tools in capturing structural responses related to steel connections. A further objective involves analyzing structural stability indicators within steel frameworks modeled in ETABS and STAAD Pro. These indicators include displacement patterns, stress concentrations, load transfer mechanisms, and potential instability conditions within structural members and connections. By examining these variables, the study seeks to establish a quantitative understanding of how steel connection behavior influences the overall structural stability of steel frameworks. The research ultimately focuses on developing a computational modeling framework that systematically evaluates steel connection behavior and stability performance through advanced structural analysis tools, generating quantitative evidence that supports improved understanding of steel structural performance.

LITERATURE REVIEW

The literature review section provides a systematic examination of existing scholarly work related to the computational modeling of steel connection behavior and structural stability in steel frameworks. In structural engineering research, literature reviews serve the purpose of identifying theoretical foundations, methodological approaches, analytical tools, and empirical findings that shape current understanding of structural behavior. Steel structures represent one of the most widely used structural systems in modern infrastructure, including high-rise buildings, industrial facilities, bridges, and transportation networks (Singh, 2017). The stability and reliability of these systems depend largely on the performance of steel connections, which act as the critical interfaces that transfer forces between structural members. Understanding the mechanical response of these connections has therefore become an essential focus of structural engineering research. Research on steel connection behavior has evolved significantly with the advancement of computational modeling techniques and structural analysis software. Traditional structural analysis methods relied heavily on simplified analytical models and experimental testing to evaluate connection performance. These approaches provided foundational insights into structural mechanics and connection design principles. Structural systems have grown increasingly complex, incorporating sophisticated architectural forms, high-strength materials, and multi-hazard loading conditions. The complexity of modern structural systems has increased the demand for advanced computational modeling tools capable of simulating detailed structural responses under various loading scenarios (Huang et al., 2021). The integration of numerical methods such as finite element analysis has allowed engineers and researchers to study steel connections with greater precision and efficiency. Computational modeling software such as ETABS and STAAD Pro has become widely adopted in structural engineering practice and research. These platforms enable

engineers to develop three-dimensional structural models, apply different load cases, and evaluate structural responses including stress distribution, deformation patterns, and stability performance. Through these simulations, researchers can analyze how connection properties influence the overall behavior of structural systems. Quantitative modeling also allows for the investigation of structural stability indicators such as displacement limits, load transfer mechanisms, and buckling behavior. The ability to evaluate these parameters computationally has strengthened the analytical capabilities of structural engineering research (Fang et al., 2017). The literature review therefore focuses on synthesizing previous studies related to steel connection mechanics, structural stability analysis, computational structural modeling, and the application of ETABS and STAAD Pro in structural performance evaluation. The section also examines methodological approaches used in quantitative structural modeling studies, including finite element analysis, numerical simulation techniques, and performance evaluation frameworks. By organizing the literature into thematic subsections, the review highlights the progression of knowledge within the field and identifies the key analytical variables used in computational modeling of steel structures. The review also emphasizes quantitative research perspectives that analyze measurable structural parameters such as stress, strain, displacement, load distribution, and connection stiffness. These parameters provide empirical indicators of structural performance and stability, enabling researchers to evaluate structural behavior using computational simulations (Li et al., 2018). The following sections outline major research themes that form the foundation for studying steel connection behavior using advanced computing tools.

Steel Connection Behavior Modeling

Structural steel has long been recognized as a fundamental material in modern infrastructure due to its predictable mechanical behavior, durability, and high load-bearing capacity. The mechanical properties of structural steel, including yield strength, tensile strength, elasticity, ductility, and toughness, significantly influence the performance of steel connections within structural frameworks. These properties determine how steel members and their connections respond when subjected to external loads such as gravity, wind, and seismic forces (Zhang et al., 2021). The quantitative evaluation of these material characteristics plays a critical role in understanding connection behavior because variations in material strength or elasticity can alter stress distribution and load transfer mechanisms within structural systems. Structural engineering studies have emphasized that the mechanical properties of steel components directly affect the stiffness and strength of connection assemblies, particularly in bolted and welded joints where material deformation influences connection rotation and load redistribution. Research in structural mechanics has demonstrated that the reliability of steel structures depends heavily on the accurate representation of material properties during structural analysis. Structural steel is generally characterized by a linear elastic response at low stress levels followed by yielding and plastic deformation as stresses increase. This predictable behavior allows engineers to design structures that can sustain loads while maintaining structural integrity. Material properties such as modulus of elasticity influence how structural members deform under applied forces, while yield strength determines the maximum stress level before permanent deformation occurs. Quantitative modeling of these material parameters provides essential insights into the behavior of steel connections under different loading scenarios (Chi et al., 2017). The influence of steel material properties extends to connection components such as bolts, welds, and connection plates. Bolted connections depend on bolt strength and frictional resistance between steel surfaces, while welded connections rely on the strength of the weld metal and the heat-affected zone. Structural mechanics research has shown that variations in steel material composition, fabrication processes, and quality control can affect the mechanical performance of connection components. Quantitative evaluation of these parameters allows engineers to determine the load-carrying capacity of connections and assess their ability to maintain structural stability during service conditions. Engineering design standards and international building codes emphasize the importance of incorporating accurate material properties into structural analysis models. Computational tools used in structural engineering integrate these material parameters into numerical simulations, allowing engineers to analyze structural performance with high levels of precision (Wang et al., 2019). Through the quantitative assessment of mechanical properties, engineers can predict how steel connections behave under different load combinations and identify potential areas of structural weakness within complex
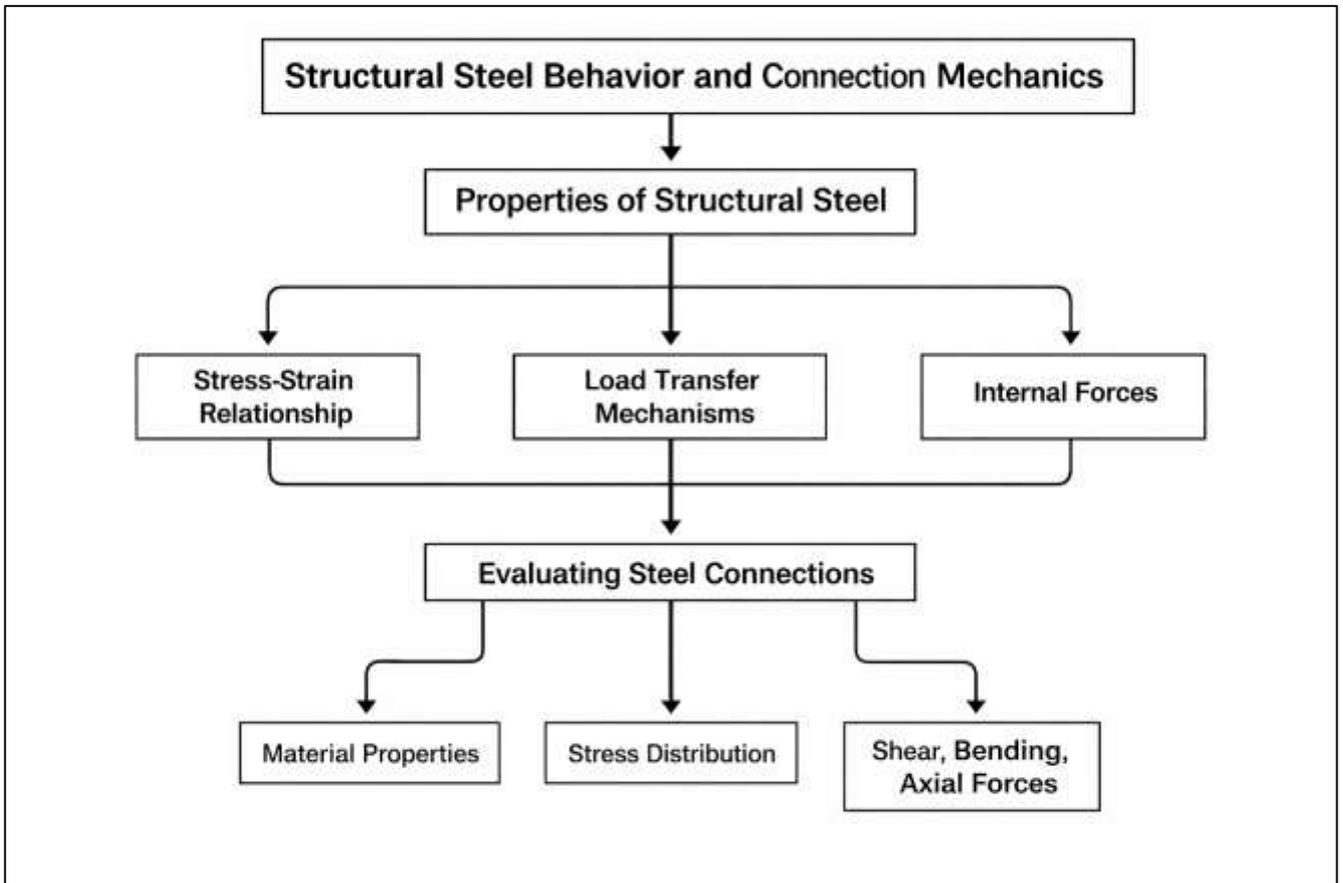
structural systems.

The stress–strain relationship represents one of the most fundamental concepts in structural mechanics and plays a critical role in evaluating the behavior of steel structural members and their connections. Stress refers to the internal resistance developed within a material when external forces are applied, while strain represents the deformation experienced by the material as a result of these forces. The relationship between stress and strain provides essential insights into the mechanical behavior of structural steel, enabling engineers to assess how steel components respond to different loading conditions (Aşıkoğlu et al., 2019). Quantitative analysis of this relationship allows structural engineers to evaluate the elastic and plastic behavior of steel members, which directly influences the performance of structural connections. Structural steel exhibits a well-defined stress–strain behavior characterized by an initial elastic region followed by yielding and plastic deformation. In the elastic region, deformation is proportional to applied stress, and the material returns to its original shape once the load is removed. When stress exceeds the yield strength of steel, plastic deformation occurs, meaning the material undergoes permanent changes in shape. This mechanical behavior plays a crucial role in the design of steel structures because it determines the load-carrying capacity of structural members and their connections. Quantitative modeling of stress–strain relationships allows engineers to evaluate how structural components distribute loads and how deformation propagates throughout a structural system. In steel connection analysis, stress–strain relationships are particularly important because connections often experience complex combinations of forces including shear, tension, and bending (Brunesi & Nascimbene, 2017). These forces create localized stress concentrations within connection components such as bolts, welds, and plates. Quantitative analysis enables engineers to identify these stress concentrations and evaluate whether the connection can safely withstand the applied loads. Research has shown that accurate representation of stress–strain behavior improves the reliability of structural models and enhances the prediction of connection performance. Advanced computational modeling techniques allow engineers to incorporate stress–strain behavior into numerical simulations of structural systems. Structural analysis software uses these material models to simulate deformation patterns, stress redistribution, and potential failure mechanisms within steel structures. Through quantitative analysis of stress–strain relationships, engineers can better understand how steel members interact within structural frameworks and how connections influence the overall performance and stability of the system (Cai et al., 2021).

Load transfer mechanisms represent a critical aspect of structural engineering because they determine how forces are distributed throughout a structural system. In steel frameworks, loads applied to structural members must be effectively transferred through connections between beams, columns, and other structural components. These connections serve as the primary pathways through which forces such as axial loads, shear forces, and bending moments move across the structural system (H. Li et al., 2017). Quantitative understanding of load transfer mechanisms is essential for evaluating the performance and safety of steel structures. Steel beams typically carry loads generated by floor systems, equipment, or environmental forces, while columns transmit these loads to the foundation. The connection between beams and columns therefore plays a central role in maintaining structural continuity and stability. Structural engineering research has demonstrated that the efficiency of load transfer depends on several factors including connection geometry, bolt arrangement, weld configuration, and plate thickness. Quantitative modeling allows engineers to evaluate how these parameters influence the distribution of forces within connection components (Shi et al., 2017). The transfer of loads within steel connections involves complex interactions between different structural elements. For example, shear forces may be transferred through bolts or welds, while bending moments may be resisted by flange plates or stiffeners. These interactions create multidirectional force paths that influence the overall behavior of the structural frame. Quantitative analysis enables engineers to trace these force paths and determine how loads propagate through structural members and connections. Understanding load transfer mechanisms is particularly important for preventing structural failures. Historical studies of structural collapses have often identified connection failure as a contributing factor, highlighting the importance of accurate load transfer modeling (Polastri et al., 2018). Through detailed quantitative evaluation, engineers can identify potential weaknesses in connection design and improve structural performance. Computational modeling tools provide the ability to simulate these

load transfer processes within complex structural systems, offering valuable insights into the interaction between beams, columns, and connection components.

Figure 3: Structural Steel Behaviour and Connection Mechanics

Mathematical modeling plays an essential role in structural engineering by enabling engineers to analyze internal forces that act within structural systems. Steel connections are subjected to multiple types of internal forces, including shear forces, bending moments, and axial forces. These forces influence the mechanical behavior of connections and determine how loads are transmitted between structural members. Quantitative modeling techniques allow engineers to represent these internal forces within structural analysis frameworks, providing insights into connection performance and structural stability (Li et al., 2020). Shear forces occur when loads cause adjacent sections of a structural element to slide relative to each other. In steel connections, shear forces are commonly transferred through bolts, welds, or shear plates that resist the sliding motion between connected members. Bending moments occur when loads create rotational effects that cause structural members to bend. These moments generate tension and compression forces within connection components, influencing their strength and stiffness. Axial forces act along the longitudinal axis of structural members and can produce either tension or compression within connection assemblies. The interaction between shear forces, bending moments, and axial forces creates complex stress conditions within steel connections. Quantitative analysis allows engineers to evaluate how these forces combine and how they affect connection performance (Liu & Zhang, 2019). Structural mechanics research has shown that accurate modeling of these internal forces is essential for predicting structural behavior under different loading conditions. Mathematical models provide a framework for calculating internal force distributions and assessing the load-carrying capacity of connection components. Modern structural analysis software incorporates advanced numerical methods that enable engineers to simulate the effects of internal forces within steel connections. These computational models consider material properties, connection geometry, and loading conditions to evaluate structural responses. Through quantitative mathematical modeling, engineers can analyze stress distribution, deformation patterns, and potential failure modes

within steel connections. This analytical capability enhances the accuracy of structural evaluations and supports the design of safer and more reliable steel structural systems (Zhou et al., 2017).
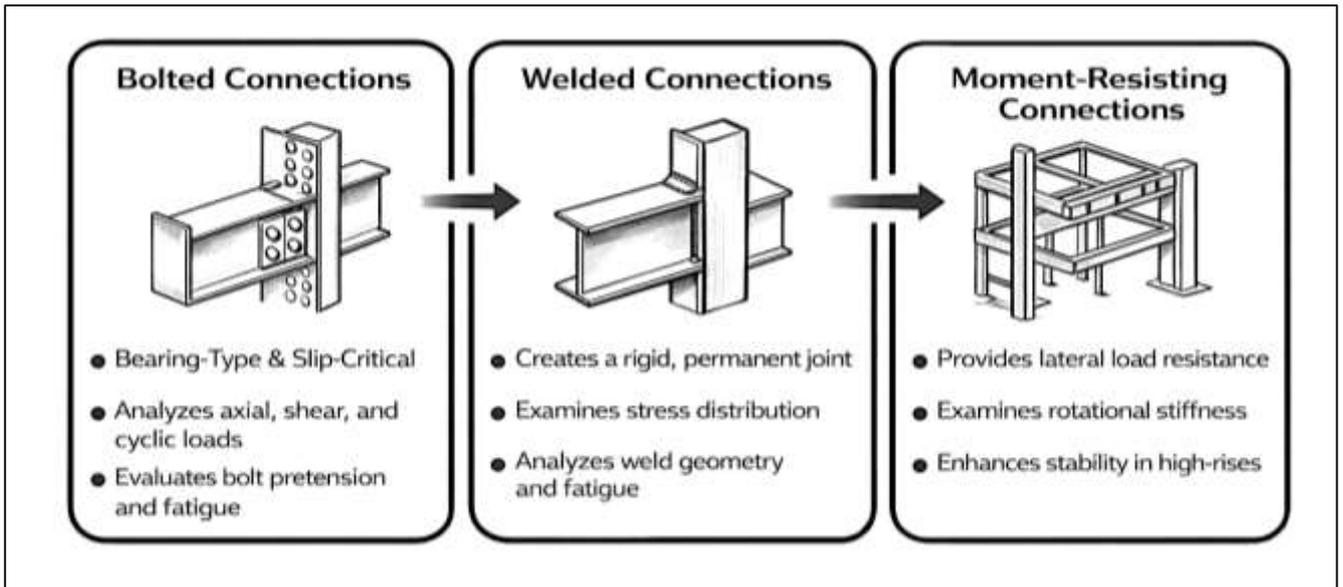
Structural Behavior of Steel Connections

Bolted steel connections represent one of the most commonly used connection systems in structural engineering due to their ease of installation, reliability, and ability to accommodate various load conditions. Structural engineers classify bolted connections based on their load transfer mechanisms, including bearing-type connections and slip-critical connections (Ke et al., 2019). The structural behavior of bolted joints depends on several factors such as bolt diameter, bolt grade, plate thickness, edge distances, and the frictional interaction between connected surfaces. Quantitative evaluation of bolted connections under static loading conditions focuses on understanding how axial forces, shear forces, and bending moments are transferred through bolt assemblies and surrounding plates. Static load analysis has demonstrated that bolt deformation, plate bearing strength, and bolt shear capacity significantly influence the load-carrying capacity of bolted joints. The performance of bolted steel connections becomes more complex under dynamic loading conditions such as seismic forces, wind loads, and vibration-induced stresses. Dynamic loads introduce cyclic stress patterns that can cause fatigue in bolt materials and gradual loosening of connection components. Research in structural engineering has emphasized that the ability of bolted connections to maintain structural integrity under repeated loading cycles is critical for the long-term stability of steel structures (Fang et al., 2017). Quantitative studies have investigated the behavior of bolted joints under cyclic loading conditions, revealing that factors such as bolt pretension, connection stiffness, and frictional resistance influence the fatigue resistance of bolted assemblies. Structural engineering research has also explored the interaction between bolt shear resistance and plate bearing behavior within connection systems. When external forces are applied to a bolted connection, stress concentrations develop around the bolt holes and within the surrounding plate material. Quantitative analysis of these stress distributions provides valuable insights into the potential for local deformation or failure within the connection region. Advanced computational modeling techniques allow engineers to simulate the behavior of bolted joints under different loading conditions and evaluate how variations in connection geometry affect structural performance. Experimental investigations and numerical simulations have contributed significantly to the understanding of bolted connection behavior (Mousavi et al., 2020). Laboratory tests have provided empirical data on bolt strength, slip resistance, and deformation characteristics, while computational models have enabled engineers to analyze large structural systems with multiple bolted connections. These studies have established quantitative frameworks for evaluating the performance of bolted steel connections and have supported the development of structural design guidelines used in modern engineering practice.

Welded steel connections represent another essential category of structural joints used in steel frameworks, particularly in applications where high structural rigidity and continuous load transfer are required. Welding involves joining steel components through localized melting and solidification of metal, creating a permanent bond between structural members. The mechanical performance of welded connections is influenced by factors such as weld size, weld geometry, welding process, and the metallurgical characteristics of the weld metal and surrounding base material. Quantitative modeling of welded connections focuses on evaluating stress distribution, deformation behavior, and load transfer mechanisms within welded joint assemblies (Liu et al., 2019). Structural engineering research has demonstrated that welded connections exhibit different mechanical behavior compared with bolted connections due to the continuous nature of the welded joint. Welded connections are capable of transferring both shear forces and bending moments with high stiffness, making them suitable for moment-resisting frames and rigid structural systems. Quantitative analysis of welded connections often examines the stress concentrations that occur at weld toes and weld roots, which are critical regions where fatigue cracks may initiate under repeated loading conditions. Understanding these stress patterns is essential for evaluating the long-term performance of welded joints. The heat generated during welding processes can alter the microstructure of steel in the heat-affected zone surrounding the weld. This metallurgical transformation can influence the mechanical properties of the material and affect the overall strength and ductility of the connection (Liu & Zhang, 2019). Quantitative studies have investigated how welding parameters such as heat input, cooling rate, and

welding technique influence the structural behavior of welded joints. These investigations have provided valuable insights into the relationship between welding processes and connection performance. Computational modeling has become an important tool for analyzing welded steel connections within structural systems. Numerical simulations enable engineers to represent complex weld geometries and evaluate how stresses develop within welded joints under different loading conditions. These models also allow researchers to investigate how welded connections interact with surrounding structural members (Baek et al., 2020). Through the integration of experimental data and computational modeling techniques, researchers have developed a deeper understanding of welded connection behavior and their role in maintaining structural stability within steel frameworks.

Figure 4: Steel Connection Behaviour and Stability

Moment-resisting steel connections play a critical role in the structural stability of high-rise buildings by providing resistance to lateral loads such as wind and seismic forces. These connections are designed to transfer bending moments between beams and columns, enabling the structural frame to resist rotational forces and maintain overall stability. In moment-resisting frames, the rigidity of beam-to-column connections allows the structure to distribute loads efficiently across multiple structural members, reducing the likelihood of localized structural failure (Li et al., 2018). Quantitative analysis of moment-resisting connections focuses on evaluating the rotational stiffness, strength, and deformation characteristics of these connection systems. High-rise buildings are particularly sensitive to lateral loads due to their height and slender structural configurations. Wind forces and seismic activity can generate significant horizontal forces that produce bending moments within structural members. Moment-resisting connections enable the structural frame to resist these forces by maintaining continuity between beams and columns. Quantitative evaluation of these connections involves analyzing parameters such as connection stiffness, rotational capacity, and energy dissipation capability during cyclic loading conditions. Research on moment-resisting steel connections has expanded significantly following observations of structural damage during major seismic events (Gao et al., 2021). Structural engineering investigations have revealed that connection performance plays a critical role in determining the ability of a building to withstand seismic forces without experiencing catastrophic failure. Quantitative studies have examined the deformation behavior of moment connections under cyclic loading conditions, highlighting the importance of connection ductility and rotational capacity in maintaining structural integrity during earthquakes. Experimental research has provided valuable insights into the behavior of moment-resisting connections through full-scale laboratory testing of beam-column assemblies. These experiments have demonstrated how connection geometry, weld configuration, and reinforcement details influence the strength and deformation characteristics of moment-resisting joints. Computational modeling has complemented experimental

work by enabling engineers to simulate the performance of moment-resisting frames within large structural systems (D'altri et al., 2020). These combined research approaches have contributed to the development of design principles that enhance the seismic resilience and structural stability of high-rise steel buildings.

Structural Stability Analysis in Steel Frame Systems

Global structural stability in multi-story steel frames refers to the capacity of the entire framing system to maintain equilibrium under vertical and lateral loading without experiencing overall sway collapse, excessive second-order deformation, or instability-driven strength loss. In the literature, this topic has been treated as a central issue in steel design because multi-story frames do not behave as isolated columns and beams, but as highly interactive systems in which member stiffness, story geometry, load path continuity, and joint behavior combine to determine overall performance (Basta et al., 2020). Scholars have shown that the stability of tall and medium-rise steel frames is strongly influenced by frame configuration, bracing arrangement, distribution of gravity loads, and the relative balance between lateral stiffness and axial demand. Research on rigid and semi-rigid framing has clarified that stability cannot be interpreted only through member strength because the redistribution of internal actions across stories may intensify instability in specific regions of a building. The literature also explains that multi-story behavior is especially sensitive to geometric nonlinearity, since the accumulation of lateral displacements across floor levels amplifies internal moments and modifies the effective resistance of columns and beam-column assemblies (Cardoso et al., 2019). Quantitative studies have therefore focused on measurable stability indicators such as interstory sway, story stiffness ratios, drift amplification, critical load levels, and internal force redistribution patterns across frame height. Comparative studies of braced and unbraced steel frames have further demonstrated that global stability depends on the coordinated action of vertical and lateral load-resisting systems rather than on the size of individual members alone. Within this body of work, modeling approaches using matrix analysis, second-order analysis, and finite element simulation have become dominant because they capture the interaction between member deformation and structural equilibrium more accurately than simplified first-order approaches (Song & Jhung, 2017). The literature consistently presents global stability as a system-level phenomenon, requiring a quantitative understanding of how structural form, load application, stiffness distribution, and connection behavior together determine the safe performance of multi-story steel buildings.

The literature on local buckling and lateral-torsional buckling has established that steel frame stability depends not only on global frame action but also on the stability of individual members subjected to compression and flexure. Local buckling refers to the instability of slender plate elements within steel sections, such as flanges and webs, while lateral-torsional buckling describes the coupled lateral displacement and twisting of beams under bending (Ferdous et al., 2019). These two forms of instability have received extensive attention because they reduce effective member strength and influence the load-carrying behavior of the entire frame. Researchers have shown that local buckling is closely related to cross-sectional slenderness, material yielding behavior, boundary restraint, and stress distribution across section components. When flange or web elements lose stability, the member may continue to carry load for a limited period, but stiffness degradation and reduced reserve capacity often alter the response of adjacent members and connections. Lateral-torsional buckling has likewise been identified as a critical issue in beams lacking adequate lateral restraint, especially in steel buildings where floor systems, bracing layouts, and connection details determine the degree of rotational and translational restraint available (Godec et al., 2020). Quantitative investigations have examined measurable variables such as unbraced length, torsional rigidity, warping restraint, moment gradient, section geometry, and residual stress effects to explain the onset and progression of buckling. Experimental and numerical studies have also shown that these instability modes interact with material nonlinearity and imperfection sensitivity, making accurate prediction dependent on realistic modeling of geometry and support conditions. The literature further indicates that local and lateral-torsional buckling do not operate in isolation; in many practical steel frames, the susceptibility of beams and columns to these forms of instability influences story stiffness, redistribution of moments, and the overall stability reserve of the structure. This has led researchers to emphasize that quantitative structural stability analysis must incorporate both member-level instability and frame-level response if steel buildings are

to be evaluated with sufficient rigor (Zhao et al., 2020).

**Figure 5: Stability Analysis of Steel Frames**
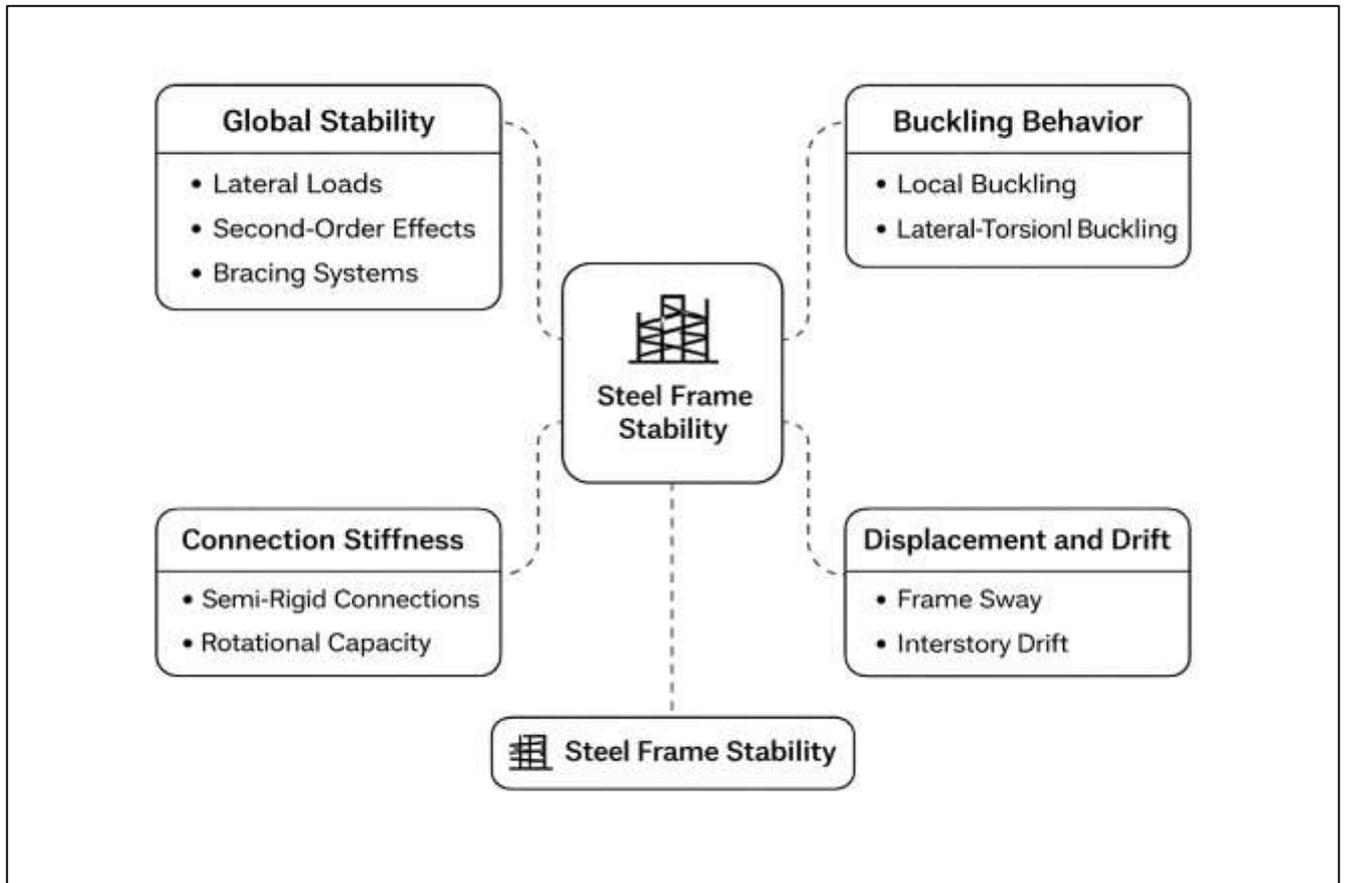
A major theme in the literature is the interaction between connection stiffness and the displacement behavior of steel frames, particularly in relation to drift control and serviceability. Connections have increasingly been recognized as active mechanical components rather than idealized pins or perfectly rigid joints, and this shift has reshaped the analysis of steel frame stability (Isayev et al., 2017). Studies on semi-rigid construction have demonstrated that connection rotational stiffness affects the distribution of moments between beams and columns, the effective lateral stiffness of a frame, and the magnitude of horizontal displacement under wind and seismic loading. In practical terms, frame drift depends not only on member sizes and bracing systems but also on the degree to which connections restrain rotation and transmit moment. Quantitative research has therefore focused on measurable parameters such as initial rotational stiffness, secant stiffness, joint deformation capacity, story displacement, interstory drift ratio, and stiffness degradation under repeated loading. The literature consistently reports that semi-rigid connections may produce larger frame displacements than rigidly assumed systems, while still offering greater continuity and redundancy than purely pinned systems (Dulo et al., 2021). This intermediate behavior is especially important in steel buildings where displacement limits govern design decisions related to nonstructural damage, occupant comfort, and overall frame stability. Several studies have shown that inaccurate assumptions regarding joint stiffness can lead to underestimation or overestimation of building drift, affecting both serviceability assessment and strength evaluation. Researchers have also connected displacement behavior to P-delta effects, noting that increased drift amplifies internal moments and can accelerate instability under combined gravity and lateral actions. As a result, structural displacement and drift have been treated in the literature as critical quantitative outputs of stability analysis, closely tied to the realistic representation of connection behavior (Reif et al., 2021). This body of research supports the view that frame stability in steel buildings is strongly governed by the interaction between connection stiffness, member flexibility, and lateral deformation demands across the height of the structure.

Finite Element Modeling Approaches for Quantitative Steel Connection Analysis

Finite element modeling has become one of the most influential analytical approaches for investigating the behavior of steel structural components and their connections under complex loading conditions. In the literature, the discretization process is treated as the foundation of any reliable finite element model because it determines how accurately a physical structural component can be represented in numerical form. Discretization involves dividing beams, columns, plates, weld regions, bolts, and stiffeners into smaller elements so that local and global responses can be evaluated in detail (Hassanieh et al., 2017). Researchers have shown that the selection of element type strongly affects the quality of results, particularly in steel connection analysis where localized stress gradients and geometric discontinuities are common. Beam elements are frequently used for frame-level modeling because they are computationally efficient and effective for representing overall member behavior, while shell and solid elements are more appropriate for capturing local stress concentrations, plate bending, bolt-hole interaction, and connection deformation patterns. The literature also emphasizes that mesh density is a critical issue in steel modeling, since a coarse mesh may overlook important stress variations around bolt holes, weld toes, and plate edges, while an excessively refined mesh may increase computational cost without proportionate analytical benefit (Yan & Rasmussen, 2021). Several studies have compared structured and unstructured meshing strategies, concluding that refined local meshing near highly stressed regions improves predictive capability while maintaining feasible model size. Investigations into contact surfaces, boundary idealization, and node compatibility have likewise shown that discretization is not merely a geometric exercise but a mechanical representation of load transfer paths within steel assemblies. As a result, the literature consistently treats discretization methods as essential to quantitative steel connection analysis because they govern the numerical stability, convergence behavior, and physical realism of finite element simulations across both member-scale and joint-scale applications (Katwal et al., 2018).

Figure 6: Finite Element Modelling of Steel Connections
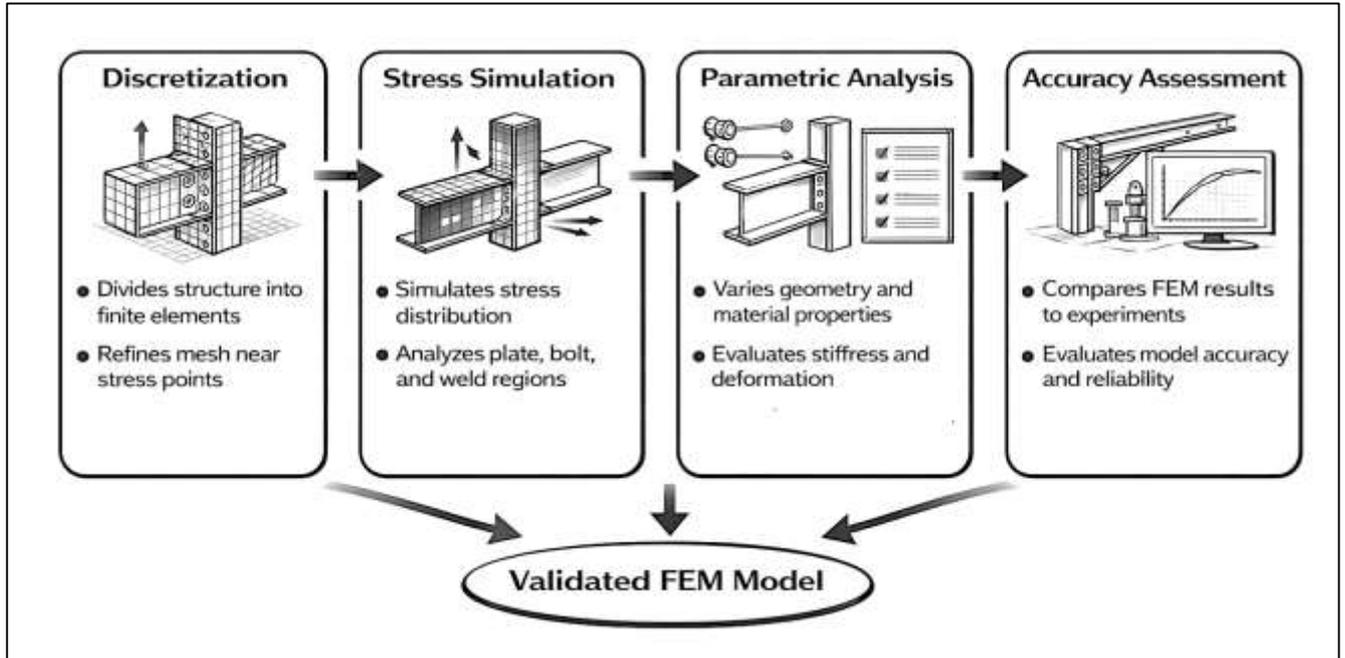
A major stream of literature in finite element–based steel connection research focuses on the numerical simulation of stress distribution in connection plates, bolts, and associated load transfer zones. Steel connections are characterized by localized force introduction, abrupt geometric transitions, and material interaction between multiple components, which makes stress distribution highly nonuniform and difficult to capture through simplified approaches (Richert & Huber, 2018). Finite element simulation has therefore been widely used to study how stresses develop around bolt holes, along plate edges, through bolt shanks, and across bearing and contact regions. The literature indicates that

connection plates often experience complex combinations of tension, shear, bending, and localized bearing stresses, especially in bolted lap joints, end-plate connections, and gusset plate assemblies. Researchers have shown that finite element models allow these complex stress fields to be visualized and quantified with far greater resolution than conventional hand-based methods. In bolted connections, simulations have been used to evaluate stress redistribution caused by bolt pretension, slip behavior, contact pressure, and interaction between fasteners and surrounding steel plates. The literature further explains that the accuracy of these simulations depends heavily on how contact mechanics, frictional behavior, and bolt preload are represented in the numerical model (David Müzel et al., 2020). Studies comparing simplified bolt representation with detailed three-dimensional bolt modeling have demonstrated that higher-fidelity approaches are more effective in capturing local stress peaks and deformation compatibility near connection interfaces. The stress patterns revealed in these models have been particularly valuable for understanding the initiation of plate yielding, bolt shear demand, local crushing, and fatigue-sensitive zones in repetitive loading conditions. Through this body of work, numerical stress simulation has emerged as a central theme in the finite element literature because it provides a quantitative basis for evaluating how steel connection components resist and redistribute forces within structurally critical regions (Chi et al., 2017).

The literature on finite element modeling of steel connections places strong emphasis on parametric analysis as a method for understanding how variations in geometry, material properties, and connection detailing influence structural response. Parametric studies are widely used because steel connections are not governed by a single variable; their performance depends on the interaction of plate thickness, bolt spacing, edge distance, weld size, stiffener arrangement, material grade, and support conditions (Zhang et al., 2019). Finite element models provide a controlled environment in which these parameters can be varied systematically and their effects on stress distribution, stiffness, deformation, and ultimate resistance can be quantified. Researchers have used this approach to identify which geometric characteristics most strongly influence connection rigidity and which material assumptions alter failure patterns or deformation concentration. The literature shows that such studies are particularly useful for distinguishing between parameters that have dominant structural influence and those whose effects are comparatively modest. At the same time, model validation is consistently presented as an indispensable part of finite element research. Numerical results are commonly validated against experimental test data, previously published benchmark studies, and recognized design provisions to confirm that simulated behavior aligns with observed structural performance (Liu et al., 2020). The validation process often includes comparison of load-deformation curves, failure modes, stress concentrations, and connection stiffness values. Studies have shown that without careful validation, even sophisticated finite element models may produce misleading results due to incorrect contact assumptions, unrealistic constraints, or oversimplified material behavior. As a result, the literature treats validation not as a final check but as an integral stage in model development. This synthesis highlights that parametric analysis and model validation are closely connected within quantitative steel connection research, since reliable variation-based findings depend on a numerical model whose assumptions have already been demonstrated to represent the physical response of steel connections with acceptable consistency (Pirdayr et al., 2021).

Accuracy assessment occupies a central place in the literature because the usefulness of finite element modeling ultimately depends on how well predicted responses correspond to actual structural behavior. In steel connection analysis, accuracy is typically evaluated by examining the model's ability to reproduce measurable outcomes such as stiffness, displacement, rotation, stress concentration, load-carrying capacity, and failure sequence (Spathopoulos & Stavroulakis, 2020). Scholars have shown that model accuracy is influenced by a range of interconnected decisions, including element formulation, mesh refinement strategy, constitutive material modeling, geometric nonlinearity, contact representation, and boundary condition definition. Research comparing two-dimensional and three-dimensional models has demonstrated that simplified approaches may be adequate for capturing general trends in stiffness and global force transfer, while more refined three-dimensional simulations are usually required to predict local yielding, bolt interaction, prying action, and plate deformation with higher precision. The literature also notes that assumptions related to steel plasticity, residual stress, initial imperfection, and bolt pretension can significantly affect predictive quality, particularly

when the model is intended to capture progressive nonlinear response (Engen et al., 2017). Accuracy assessment studies frequently report that convergence testing and sensitivity analysis are important for separating true structural behavior from numerical artifacts created by modeling choices. In addition, comparisons between finite element predictions and laboratory observations have shown that the most credible models are those that reproduce both global and local response characteristics, rather than matching only a single output such as ultimate strength. The literature therefore presents accuracy assessment as a multidimensional evaluation process rather than a binary judgment of success or failure. Across reviewed studies, the consensus is that finite element models can predict steel connection behavior with high reliability when they are developed using appropriate discretization, realistic mechanical assumptions, and rigorous validation procedures (Biegler et al., 2018). This has made finite element analysis a leading quantitative tool for studying steel structural behavior in both academic research and engineering practice.

Quantitative Structural Modeling Using ETABS

ETABS has become one of the most frequently discussed software environments in the literature on three-dimensional modeling of steel buildings because it offers an integrated platform for representing the geometric, material, and load-resisting characteristics of multistory structural systems within a single computational framework (Sampaio & Gomes, 2021). The literature generally describes ETABS as especially suitable for building-type structures due to its story-based modeling logic, matrix-based analytical engine, and ability to organize members, diaphragms, mass distributions, and lateral-force-resisting systems in a form that aligns with practical steel building design. Researchers examining steel structures through ETABS have emphasized that three-dimensional modeling allows the engineer to capture the spatial interaction between beams, columns, braces, floor systems, and core elements rather than treating the building as a collection of disconnected two-dimensional frames. This is especially important in steel buildings where plan irregularity, torsional effects, differential stiffness between stories, and nonuniform gravity and lateral loading create responses that cannot be represented adequately in simplified models (Ciotta et al., 2021). The literature also shows that ETABS-based modeling supports the quantitative evaluation of global frame action by allowing the analyst to assign realistic boundary conditions, diaphragm assumptions, member releases, and section properties to simulate the structural behavior of high-rise and medium-rise steel buildings under practical design conditions. Several studies have used ETABS to compare different framing systems, bracing configurations, and member layouts, finding that the accuracy of three-dimensional representation strongly affects the prediction of internal forces, lateral displacement, torsional behavior, and story-level demand. In this body of work, ETABS is not treated merely as a drafting interface but as a computational environment in which building behavior is translated into measurable outputs through a structured analytical model (Radkia et al., 2020). The literature therefore presents three-dimensional ETABS modeling as a central methodological step in quantitative steel building analysis because it links structural configuration directly to the numerical evaluation of system behavior, performance, and stability.

A major theme in the ETABS literature concerns the simulation of multiple load cases, particularly gravity, wind, and seismic actions, because the reliability of a steel building model depends on how comprehensively loading scenarios are represented in the analytical process. Researchers have consistently shown that ETABS is widely used for the generation and combination of static and dynamic load cases, allowing engineers to examine how steel building frames respond to vertical service loads, lateral environmental effects, and earthquake-induced inertia forces within the same model (Abdel Raheem et al., 2018). In studies of gravity loading, ETABS has been used to quantify beam moments, column axial loads, floor deflections, and load path continuity across stories, helping researchers evaluate how dead and live loads influence the base structural demand before lateral effects are introduced. The literature on wind simulation highlights the importance of ETABS in capturing lateral story shears, overturning moments, torsional irregularity, and drift response, especially in tall steel buildings where wind effects can dominate serviceability considerations. Seismic simulation has received even greater attention, with studies using equivalent static procedures, response spectrum analysis, and time-history approaches to investigate story acceleration, base shear, interstory drift, and force redistribution in steel lateral systems (Wang et al., 2021). Across these studies, ETABS is

repeatedly described as valuable for quantitative comparison because it permits the analyst to apply code-based loading protocols and examine how different structural systems respond under the same loading framework. The literature further explains that the simultaneous consideration of gravity and lateral actions is essential because combined loading changes member demand, frame stiffness utilization, and overall stability behavior (Archana & Akbar, 2021). In this sense, ETABS-based load simulation has been presented as an important methodological tool for moving beyond isolated force calculations and toward a building-wide understanding of how multiple load environments affect structural performance in measurable and comparable ways.

Figure 7: ETABS Based Steel Frame Analysis
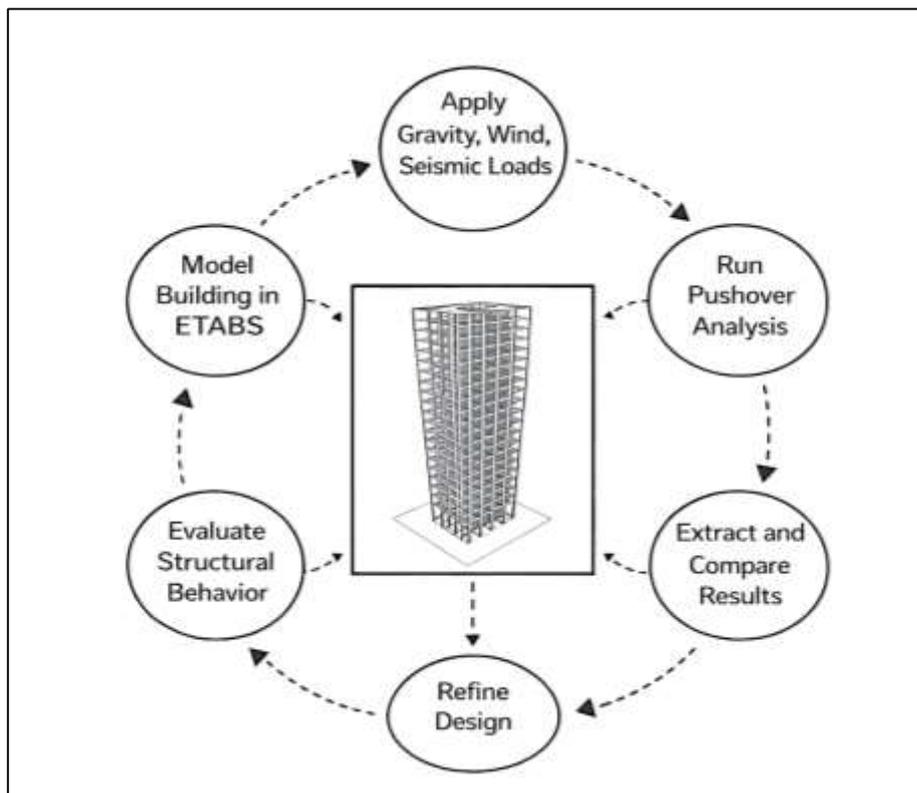
The literature on ETABS-based steel building analysis places strong emphasis on displacement and drift because these outputs are among the most informative quantitative indicators of structural response under service and extreme loading conditions. Researchers have widely used ETABS to examine lateral displacement patterns, story drift ratios, roof displacement, torsional displacement, and deformation compatibility between structural components in multistory steel frames (Kassem et al., 2019). These measures are important not only because they reflect serviceability performance, but also because they provide insight into the stiffness distribution and load-resisting efficiency of the entire structural system. Studies comparing different steel framing layouts, bracing systems, and member proportions have shown that ETABS simulations are particularly effective for identifying vertical irregularities, soft-story tendencies, and stiffness imbalances that contribute to excessive drift. In the literature, displacement results generated by ETABS are often interpreted together with frame behavior, since the magnitude and distribution of deformation reveal how gravity frames, moment frames, and braced systems interact across the building height (Pinzón et al., 2021). This has led many researchers to use ETABS outputs to assess whether certain stories attract disproportionately high drift demand or whether torsional response causes uneven deformation at the plan level. Another recurring issue in the literature is the role of connection assumptions in shaping frame behavior. Although ETABS is often used with idealized joint conditions, many studies acknowledge that assumptions regarding rigid and semi-rigid connectivity influence moment distribution, effective frame stiffness, and displacement prediction. As a result, ETABS-based drift analysis is commonly treated not as a simple

code-check exercise, but as a quantitative method for understanding the dynamic relationship between structural configuration, connection behavior, and lateral response (Lee et al., 2018). Through this literature, ETABS emerges as a widely used platform for translating the physical behavior of steel frames into measurable displacement-based indicators that support the evaluation of performance and structural adequacy.

Quantitative Structural Modeling Using STAAD Pro

The literature on structural engineering software consistently identifies STAAD Pro as one of the most established platforms for three-dimensional modeling of steel structural frames, particularly in the analysis of buildings, industrial sheds, transmission structures, towers, and other complex steel systems. Scholars describe three-dimensional modeling in STAAD Pro as an important advancement over simplified planar analysis because steel structures rarely behave in only one direction under service and extreme loading conditions (Ponnada & Reddi, 2020). In real structural systems, beams, columns, braces, and connections interact spatially, producing combined responses that are governed by geometry, support conditions, and member continuity. STAAD Pro has been widely used in the literature because it allows engineers to create integrated analytical models in which frame members, nodal restraints, section properties, and material characteristics can be assembled into a realistic representation of structural behavior. Research comparing manual methods with software-based modeling has shown that three-dimensional STAAD Pro simulations improve the ability to capture secondary effects, torsional response, frame interaction, and load redistribution across the entire structural system (Ishack et al., 2021). A recurring theme in the literature is that the usefulness of STAAD Pro lies not only in its computational speed but also in its ability to represent the interdependence of structural members under multi-directional force transfer. Studies on multistory steel buildings and industrial steel frameworks indicate that three-dimensional modeling enhances the prediction of structural response by accounting for member alignment, support eccentricities, and the connectivity of load-resisting subsystems. The literature also emphasizes that the quality of a STAAD Pro model depends on accurate geometric idealization, appropriate assignment of member properties, and correct representation of supports and releases (Bhowmik & Chakraborti, 2020). In this sense, three-dimensional frame modeling is treated as the starting point for all subsequent quantitative analysis because the reliability of structural outputs depends directly on how faithfully the steel system has been represented in the computational environment.

Figure 8: STAAD Pro Steel Frame Analysis
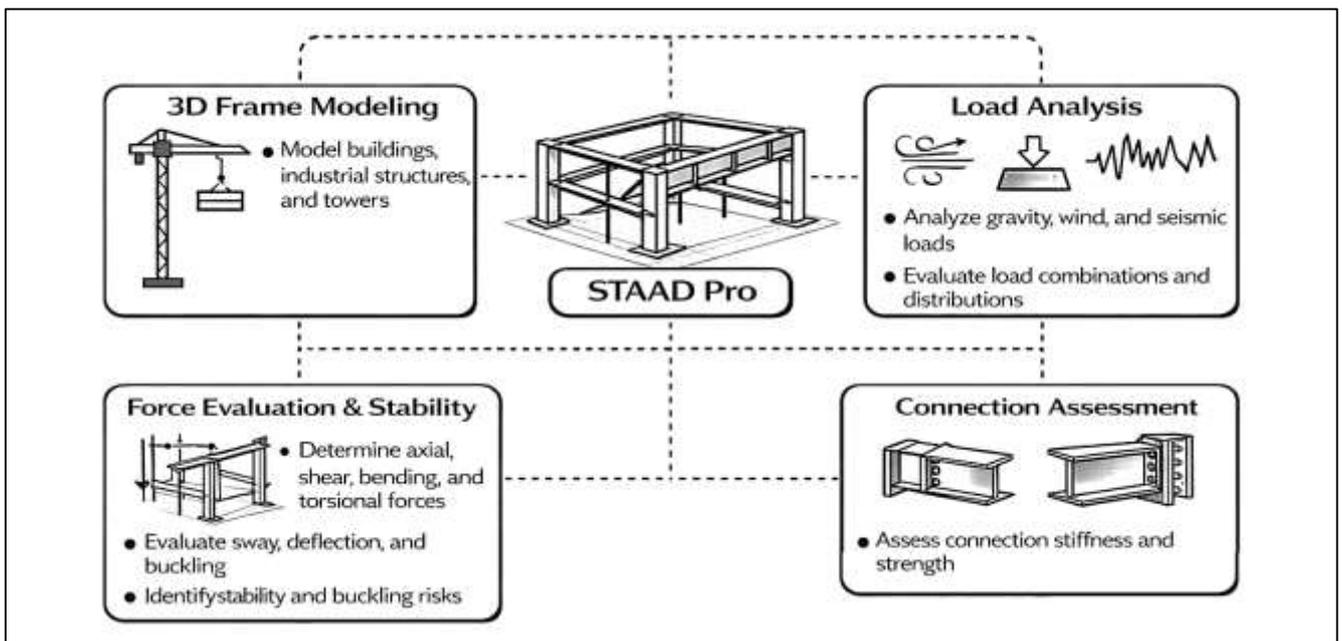
Load analysis is one of the most widely discussed applications of STAAD Pro in the literature, especially in studies involving steel structures subjected to gravity, wind, seismic, and combined

loading conditions. Researchers have consistently used the software to quantify how structural systems respond to multiple load cases and combinations, allowing for a more complete assessment of steel building performance than would be possible through isolated manual calculations (Archana & Akbar, 2021). In gravity load analysis, STAAD Pro has been applied to determine beam moments, column axial forces, support reactions, and load transfer paths in steel frames carrying dead and imposed loads. The literature shows that these outputs are essential for understanding the base demand condition of the structure before environmental effects are introduced. Wind load studies using STAAD Pro often focus on lateral displacement, overturning action, member force amplification, and directional sensitivity in tall and slender steel frames. Seismic analysis has also received strong attention, with scholars using STAAD Pro to assess dynamic response, lateral force distribution, base shear development, and interstory deformation under earthquake loading protocols (Alisibramulisi et al., 2019). Across these studies, the software is valued for its capacity to simulate several load scenarios within the same model and generate quantitative outputs that support comparison among alternative structural configurations. The literature further indicates that the interaction of vertical and lateral loads is particularly important in steel systems because combined load effects influence frame sway, second-order response, and member demand. Many researchers therefore present STAAD Pro as an efficient tool for evaluating realistic design situations where steel structures must resist concurrent loading rather than idealized single-force conditions (Ohta et al., 2019). The synthesis of these studies shows that quantitative load analysis in STAAD Pro serves both a design and research purpose, enabling engineers to interpret how structural geometry, stiffness distribution, and load combinations affect the overall response of steel frameworks in measurable and analytically consistent ways.

A major area of discussion in the literature concerns the ability of STAAD Pro to generate quantitative information on stress distribution and member force behavior throughout steel structural systems. Researchers have used the software extensively to compute axial forces, shear forces, bending moments, torsional effects, and support reactions in beams, columns, and bracing members, providing a detailed understanding of how loads are transmitted through the structural frame (Calabria et al., 2020). This capability has been particularly valuable in the assessment of steel buildings and industrial structures where force flow is not uniform and where certain members may attract disproportionate demand because of geometry, stiffness variation, or load eccentricity. The literature often interprets member-force results together with stress behavior, noting that the calculated internal actions provide the basis for judging whether individual members remain within acceptable strength and serviceability limits. In studies of structural stability, STAAD Pro has also been employed to evaluate sway behavior, deflection patterns, and buckling sensitivity in steel systems (Concepcion & Ilagan, 2019). Researchers frequently highlight that steel frames are vulnerable to instability not only because of member slenderness but also because of the interaction between axial compression, flexural response, and lateral displacement under combined loading. STAAD Pro has therefore been used in the literature to examine how global frame instability may emerge from local force intensification and stiffness reduction. Studies on buckling behavior have shown that the software can assist in identifying compression members and frame regions that are most susceptible to instability under practical load combinations. This has made STAAD Pro an important analytical environment for examining the relationship between internal force development and broader structural performance (Zhong et al., 2020). The literature thus presents the evaluation of stress distribution, member forces, and stability as interconnected tasks, since force patterns reveal the mechanical condition of the frame while displacement and buckling indicators show whether the structure can preserve equilibrium under increasing demand.

The literature also recognizes STAAD Pro as a useful platform for the broader performance assessment of steel connections within frame-level structural analysis, even though local connection detailing may sometimes require supplemental finite element investigation. In many reviewed studies, researchers use STAAD Pro to assess how connection assumptions influence global frame behavior, member-end forces, rotational compatibility, and the overall response of steel buildings and industrial frames (Thalange et al., 2017). This approach is especially relevant in cases where connections are represented through end releases, moment continuity assumptions, or partially restrained behavior that affects stiffness distribution across the structure. Scholars have shown that the assumed condition of beam-

column and beam-beam joints has a direct effect on the magnitude of internal forces, lateral displacement, and frame stability, which means connection behavior cannot be separated from system-level performance. In the literature, quantitative performance assessment commonly involves interpreting nodal displacements, end moments, shear transfer, axial force continuity, and overall drift patterns as indirect indicators of how the connection system contributes to structural action (Olawumi et al., 2017). Some studies have used STAAD Pro to compare alternative framing arrangements with varying joint conditions and have found meaningful differences in force redistribution and structural efficiency. Others have emphasized that the software is especially valuable in practice because it allows engineers to integrate connection-related assumptions into the same analytical model used for member design, thereby improving consistency between overall frame analysis and design evaluation. The literature further notes that while detailed local stress concentrations in plates, welds, and bolts may not be fully captured in standard frame models, STAAD Pro remains important for determining the global demands that those connections must resist (Ganesan & Ramsagar, 2021). For this reason, the software is frequently presented as a practical and analytically robust tool for evaluating connection-related structural performance at the system level, where joint behavior is interpreted through its measurable influence on stiffness, stability, internal force transfer, and deformation response.

Modeling Approaches in ETABS and STAAD Pro

Comparative literature on ETABS and STAAD Pro commonly begins by examining the computational logic that underpins each platform, since differences in modeling architecture often shape the results obtained from structural simulations. ETABS is widely discussed as a building-oriented analytical environment designed specifically for multistory structures, with strong emphasis on story-based data organization, diaphragm behavior, lateral load distribution, and integrated treatment of vertical and horizontal structural systems (Fainshmidt et al., 2020). STAAD Pro, in contrast, is often characterized in the literature as a more general-purpose structural analysis platform capable of modeling a wider variety of structural forms, including buildings, towers, industrial frames, bridges, and trusses. These distinctions have led researchers to compare how each software handles the analytical representation of steel frames, especially when the objective is to simulate connection-sensitive behavior, frame stiffness, and structural stability in a quantitative manner. The literature indicates that although both programs are grounded in matrix-based structural analysis and numerical computation, they differ in workflow structure, model idealization strategy, load-generation routines, and the extent to which building-specific behavior is embedded into the software environment (Darabi et al., 2019). Comparative studies have shown that ETABS often performs more efficiently in regular and irregular building systems because of its built-in handling of story drift, mass participation, and lateral load-resisting systems, while STAAD Pro is frequently appreciated for its flexibility in member-level assignment, broad code integration, and suitability for nonbuilding steel structures. Scholars have also noted that the treatment of end releases, member offsets, load combinations, and stiffness modifiers can vary between the two platforms, making model setup a critical factor in comparative research. As a result, the literature does not frame ETABS and STAAD Pro as competing tools in a simplistic sense; rather, it presents them as computational systems shaped by distinct analytical philosophies (Kraus et al., 2018). This has made algorithmic comparison an important part of quantitative structural research because the choice of software influences how structural behavior is discretized, interpreted, and transformed into measurable outputs relevant to steel connection and stability analysis.

A central theme in the comparative literature is the quantitative examination of structural outputs generated by ETABS and STAAD Pro, particularly displacement, internal force distribution, support reactions, and stress-related demand. Researchers have frequently used matched structural models to determine whether both software platforms produce comparable results when identical geometry, material properties, supports, and load cases are applied (Nguena Nguefack et al., 2020). These studies generally show that both platforms are capable of producing analytically reliable results for conventional steel frames, yet measurable differences often emerge in displacement magnitude, member force patterns, and the distribution of structural demand across the frame. The literature explains that such differences are usually not random, but are associated with modeling assumptions, load application procedures, meshing logic in selected cases, treatment of rigid zones, and the internal handling of second-order effects or load combinations. In multistory steel buildings, ETABS is often

reported to produce highly organized story-based displacement and drift outputs, which has made it especially useful in comparing lateral deformation patterns under wind and seismic loading. STAAD Pro, on the other hand, is often discussed as offering strong member-level force reporting and detailed tabulation of structural response, which can be advantageous when the analyst is focused on tracing force flow through beams, columns, and bracing members (Zhao et al., 2021). Comparative investigations have shown that even when overall results are broadly similar, slight variations in deflection, end moments, or axial force may influence design interpretation, especially in slender frames or systems sensitive to joint behavior. Some studies have also examined stress-related outputs indirectly through member demand ratios and section checks, observing that software-specific analysis settings can affect how critical structural regions are identified. The literature therefore emphasizes that comparative quantitative analysis is not limited to checking whether two programs yield identical numerical values (Bond-Taylor et al., 2021). It also involves understanding how each platform structures output data, highlights critical response indicators, and supports engineering judgment in the interpretation of steel frame behavior. This makes displacement and stress comparison a significant methodological issue in studies that aim to evaluate software suitability for steel structural modeling.

Figure 9: ETABS and STAAD Pro Comparison
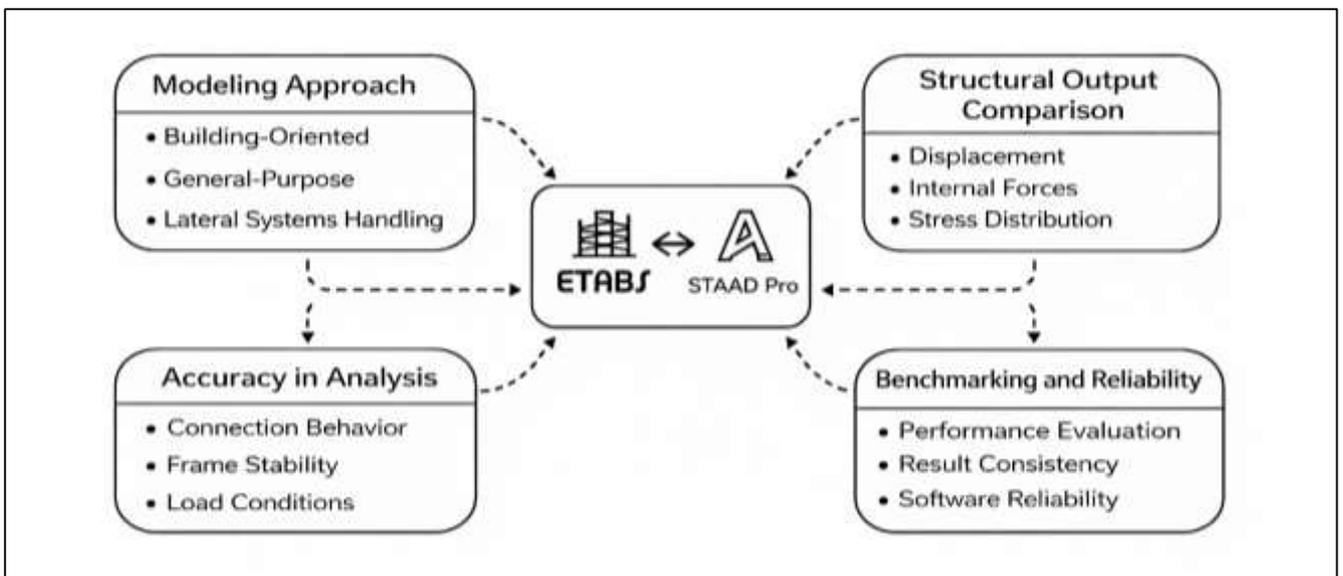
The literature comparing ETABS and STAAD Pro frequently addresses modeling accuracy in relation to steel connection behavior and system-level stability, recognizing that global software outputs are only useful when they correspond reasonably well to actual structural response. In this context, accuracy is discussed not only in terms of numerical closeness between the two platforms, but also in terms of how well each software captures the mechanical implications of connection assumptions within the broader frame (Feng et al., 2021). Steel connections are often simplified in both ETABS and STAAD Pro through idealized rigid, pinned, or partially restrained conditions, and the literature has shown that these assumptions play a major role in the prediction of frame drift, end moments, force redistribution, and stability demand. Comparative studies indicate that ETABS is often preferred in analyses where overall building response, story stiffness, modal behavior, and drift sensitivity are central concerns, while STAAD Pro is often favored where a broader range of structural configurations and detailed member force interpretation are required. Researchers have also pointed out that the modeling accuracy of either platform depends less on software brand alone and more on the analyst's ability to define realistic support conditions, connection properties, member releases, load paths, and geometric stiffness effects (Lyu et al., 2018). The literature consistently shows that when structural models are oversimplified, both programs can produce outputs that appear technically correct while still misrepresenting connection-sensitive behavior. This is especially important in steel frames where semi-rigid joint behavior can alter moment continuity and modify the overall lateral stiffness of the

structure. In comparative benchmarking studies, model accuracy has often been judged through consistency with hand verification, code-based expectations, or published analytical results. These studies generally conclude that both ETABS and STAAD Pro can achieve acceptable predictive quality for steel structural analysis, yet their performance depends strongly on modeling discipline and the appropriateness of idealization choices (Hagenauer & Helbich, 2017). The literature thus frames accuracy as a combined product of software capability and modeling judgment rather than as an inherent property of the software alone.

Performance benchmarking and reliability assessment form another major category in the comparative literature, particularly in studies evaluating ETABS and STAAD Pro as advanced tools for structural decision-making in steel engineering applications. Benchmarking studies typically compare the two programs using standard steel building models, portal frames, industrial sheds, or multistory lateral systems in order to assess computational efficiency, output consistency, convergence behavior, and sensitivity to user-defined assumptions (Kassem & Succar, 2017). The literature shows that ETABS is commonly benchmarked favorably for building-centric applications because it streamlines the analysis of floor diaphragms, story response, modal participation, and code-based lateral load procedures. STAAD Pro is often benchmarked favorably for its adaptability across varied structural forms and for the breadth of design and analysis functions available to the engineer. Reliability assessment in the literature is usually broader than benchmarking alone. It considers whether the software generates stable and interpretable results across repeated analytical scenarios and whether the outputs remain dependable when structural irregularities, alternative load combinations, or varying connection assumptions are introduced (Khosravi et al., 2019). Comparative research has found that both software platforms are reliable for conventional steel analysis when used correctly, yet their reliability is closely tied to the alignment between the software's analytical strengths and the structural problem being studied. For example, ETABS is regularly described as highly reliable in tracking drift, story-level stiffness, and lateral response in multistory steel buildings, whereas STAAD Pro is often recognized for reliable force-based analysis across more diverse steel systems. The literature also emphasizes the importance of user competence, because the same software may produce highly credible or questionable results depending on how carefully the model is assembled and checked. In this way, reliability is interpreted not as an automatic feature of advanced structural modeling tools, but as a quality emerging from the interaction between software capability, analytical assumptions, and engineering expertise (Ekstedt et al., 2019). Comparative literature therefore presents ETABS and STAAD Pro as robust but context-dependent tools whose benchmarking and reliability must be assessed in relation to the structural objectives of the study.

Indicators in Advanced Computing-Based Steel Modeling

Stress distribution metrics occupy a central position in advanced computing-based steel modeling because they provide direct quantitative evidence of how forces are transmitted, concentrated, and dissipated within structural members and their connections. In the literature, stress is not treated as a single isolated output but as a spatially variable indicator that reflects the interaction of geometry, material properties, support conditions, load intensity, and connection configuration (N. K. Singh et al., 2019). In steel structural systems, researchers have consistently emphasized that stress patterns are especially significant near discontinuities such as bolt holes, weld regions, flange-web intersections, gusset plates, stiffener terminations, and beam-column interfaces. Advanced computational platforms have allowed scholars to move beyond generalized member-force approximations and assess local and global stress behavior with far greater precision. This has enabled the identification of principal stress zones, regions of peak demand, stress gradients along member length, and the redistribution of internal actions as loading conditions change. The literature shows that stress distribution metrics are frequently used to interpret whether a structural component is behaving elastically, approaching yielding, or developing critical concentrations that may initiate local damage (Armaghani & Asteris, 2021). In connection-sensitive steel systems, these metrics are also essential because the difference between acceptable and unsafe behavior often lies in highly localized regions rather than in average member demand. Research comparing analytical, numerical, and experimental approaches has shown that advanced computing environments improve the understanding of how stress migrates across structural interfaces and how design modifications alter the severity of localized demand. This body of

literature therefore presents stress distribution metrics as fundamental quantitative indicators in steel modeling, not only for assessing member adequacy but also for revealing the mechanical logic of structural response across the entire system (Sharafati et al., 2020).

Structural deformation and displacement behavior have been widely recognized in the literature as primary indicators of how steel frameworks respond to service loads, environmental forces, and extreme loading conditions. In advanced computing-based modeling, displacement is treated as more than a geometric outcome; it is interpreted as an integrated expression of structural stiffness, load path continuity, member interaction, and connection restraint (Trong et al., 2021). Researchers have used computational modeling to quantify lateral displacement, vertical deflection, joint rotation, interstory drift, torsional movement, and localized deformation in steel structures ranging from industrial frames to multistory buildings. The literature consistently shows that these measures are essential because they link applied loading to visible structural behavior and provide a practical basis for judging serviceability, stability, and performance adequacy. Excessive displacement is often associated with stiffness imbalance, inadequate bracing, weak connection behavior, or poor distribution of lateral resistance, while controlled deformation is generally interpreted as evidence of effective structural interaction (Yaseen et al., 2020). Advanced modeling tools have made it possible to trace displacement patterns through the full structural system, revealing how movement accumulates across stories, how floor diaphragms influence frame action, and how support flexibility may alter overall response. Researchers have also examined deformation compatibility between connected members, noting that displacement behavior can expose inconsistencies in force transfer or stiffness assumptions that would not be evident from force output alone. In steel connection studies, localized deformation around joints, plates, and interface regions has been used to understand stiffness degradation and rotational behavior under loading (Qiao et al., 2020). Across the literature, deformation and displacement metrics are therefore treated as indispensable quantitative indicators because they show how structural systems actually move under demand and whether the modeled steel framework behaves in a manner consistent with safe and reliable performance.

Figure 10: Steel Stress and Deformation Analysis
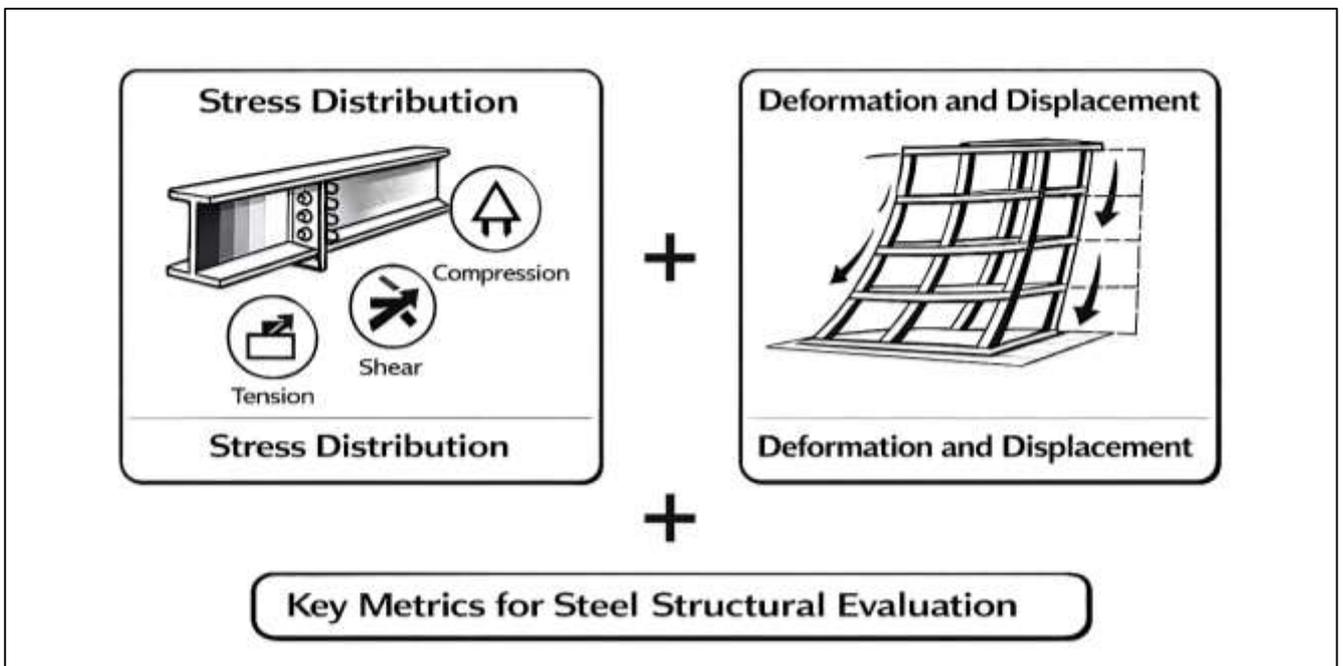
METHODS

This study adopted a quantitative comparative simulation-based research design grounded in the principles of computational structural mechanics and numerical performance evaluation. The study was designed to examine the behavior of steel connections and the stability performance of steel structural systems through advanced computing-based modeling using ETABS and STAAD Pro. A

comparative case-based analytical framework was employed because the research focused on measuring and comparing structural responses produced under controlled modeling conditions rather than observing naturally occurring field behavior. The theoretical basis of the study rested on structural analysis theory, finite element idealization, and frame stability theory, which collectively explain how internal forces, deformation, stiffness, and load transfer develop in steel systems under different loading conditions. The research design was appropriate because it enabled the generation of numerical outputs from standardized structural models and supported objective comparison across software platforms and connection conditions. The study treated the selected steel building models as analytical cases and evaluated them under identical assumptions related to geometry, material properties, boundary conditions, and load application. This design allowed the measurement of dependent structural performance variables such as displacement, drift, axial force, bending moment, stress distribution, and stability-related responses. The independent analytical factors included connection condition, loading scenario, and software platform. The methodological orientation was nonexperimental in the conventional human-subject sense, yet it followed a structured quantitative procedure comparable to experimental design because all model inputs were systematically controlled and the resulting outputs were statistically examined. The framework also reflected engineering performance assessment logic in which structural adequacy was evaluated through measurable indicators derived from numerical simulations. In this way, the study was positioned as a comparative quantitative computational modeling study aimed at identifying differences and relationships in steel connection behavior and structural stability performance across advanced structural analysis environments.

Participants/Materials/Subjects

The study did not involve human participants. The units of analysis consisted of steel structural frame models and steel connection configurations developed for simulation in ETABS and STAAD Pro. The materials included representative multistory steel building frames, beam-column connection arrangements, and associated structural properties required for computational analysis. A purposive sampling strategy was used to select the structural models because the study required cases that were relevant to the objectives of evaluating steel connection behavior and frame stability in building-type systems. The selected models represented regular steel frame structures that could be consistently reproduced in both software platforms and subjected to identical loading scenarios. Purposive selection was appropriate because the study sought analytically comparable structural cases rather than random physical specimens. The inclusion criteria required that the selected structural models: (a) were steel frame building systems suitable for three-dimensional modeling, (b) contained beam-column connection regions relevant to moment transfer and stability analysis, (c) could be modeled completely in both ETABS and STAAD Pro without loss of analytical consistency, (d) included sufficient geometric and material detail to allow quantitative extraction of displacement, internal force, and stability outputs, and (e) were compatible with gravity, wind, and seismic load simulation. Models were included because they allowed direct comparison of software-generated responses under equivalent analytical conditions. The exclusion criteria eliminated structural systems with incomplete geometric data, highly irregular hybrid systems requiring specialized nonlinear local joint modeling beyond the scope of both platforms, and models lacking compatibility with both software environments. Connection arrangements that could not be represented consistently across both platforms were also excluded. The final analytical sample therefore consisted of a set of standardized steel structural models with predefined connection conditions, material properties, and loading cases. These models served as the computational subjects through which the behavior of steel connections and stability performance were quantitatively evaluated.

Instrumentation/Data Collection Tools

Data were collected using ETABS and STAAD Pro as the primary structural modeling and analysis instruments. These software platforms were used to construct three-dimensional steel frame models, define material and section properties, assign support conditions, apply load cases, and generate structural performance outputs. ETABS was used because of its suitability for multistory building modeling, story-wise response evaluation, and lateral load analysis. STAAD Pro was used because of its broad structural analysis capability, member-force reporting, and frame-level stability assessment

functions. Supporting tools included spreadsheet software for organizing extracted numerical outputs and statistical software such as SPSS, R, or Python for data screening, coding, and inferential analysis. The instrumentation included standard structural engineering input parameters such as steel grade, modulus of elasticity, member sections, connection assumptions, support restraints, and load combinations. Data collection sheets were prepared to record output variables from both programs in a consistent format. These variables included maximum story displacement, interstory drift, axial force, shear force, bending moment, reaction force, member utilization indicators, and selected stability-related outputs. Instrument validation was addressed through model verification and cross-platform consistency checks rather than survey reliability indices such as Cronbach's alpha, since the study did not use perceptual scales. Validation procedures included the use of identical geometry, material assignments, and loading conditions across both software environments, as well as pilot runs to ensure that the extracted outputs corresponded to the same structural locations and load combinations. Calibration was performed by reviewing model units, section definitions, support conditions, and load applications before final simulation. Output consistency was further checked by comparing basic structural reactions and undeformed model properties across both platforms prior to full analysis. These procedures strengthened measurement reliability and reduced the possibility of software-input discrepancies affecting the statistical comparison.

Figure 11: Methodology of this study
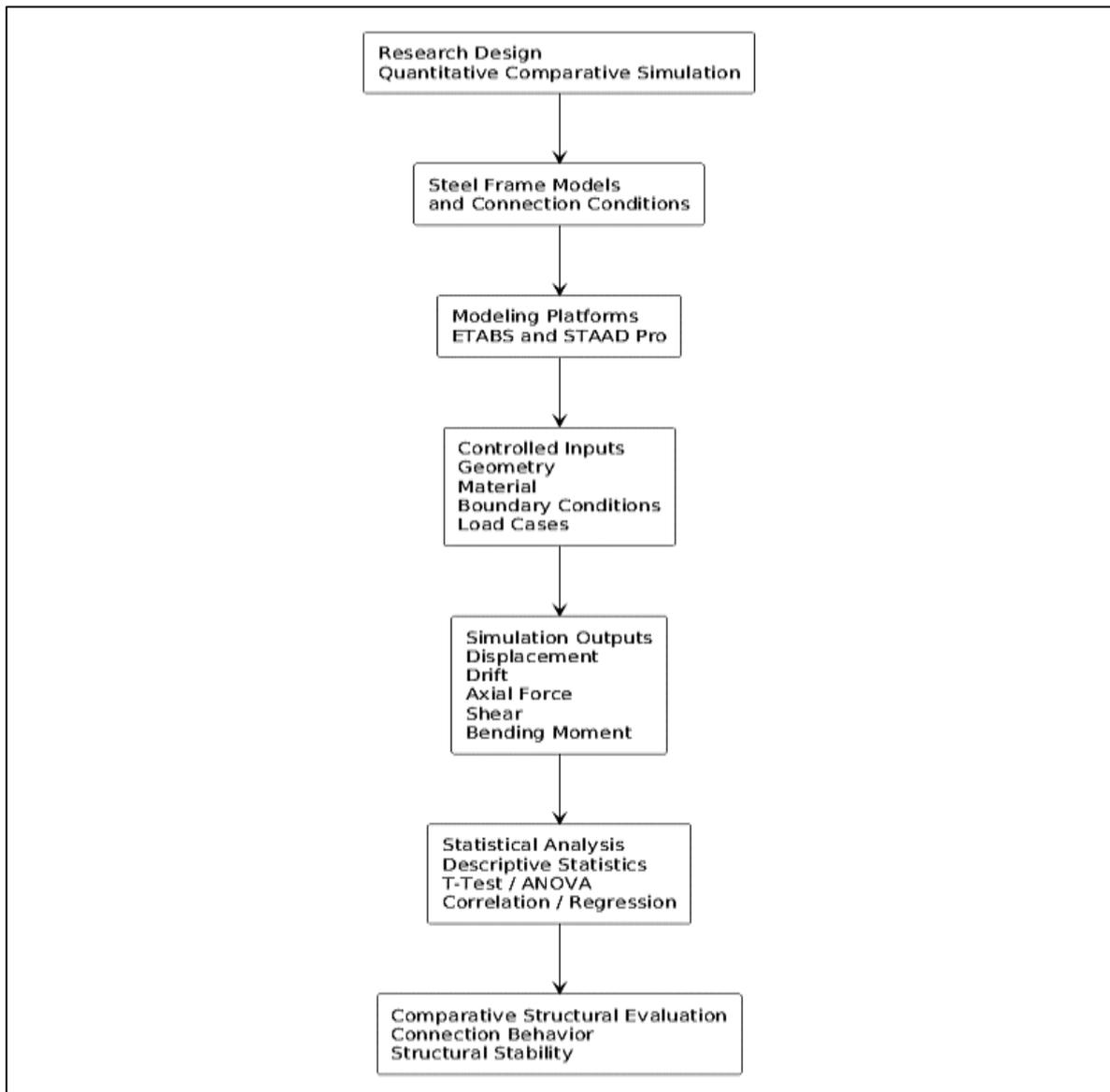
Experimental Procedure

The research was conducted in a sequential and controlled manner. First, the study objectives and analytical variables were defined, and the structural performance indicators to be examined were identified from the theoretical and literature-based framework. Second, representative steel frame building models were selected based on the inclusion criteria and translated into standardized geometric layouts suitable for both ETABS and STAAD Pro. Third, material properties for structural steel, cross-sectional dimensions of beams and columns, boundary conditions, and connection assumptions were specified using the same engineering parameters in both software platforms. Connection conditions were assigned according to the analytical purpose of the study, including rigid or partially restrained behavior where appropriate for comparison. Fourth, the three-dimensional structural models were created independently in ETABS and STAAD Pro. Each model was reviewed carefully to confirm dimensional consistency, node alignment, member connectivity, support assignments, and section property accuracy. Fifth, load cases were defined and assigned. These included gravity loads, and where relevant, wind and seismic actions based on standard building-type analytical conditions. Load combinations were then generated to reflect typical structural design scenarios. Sixth, preliminary trial analyses were run to verify that the models behaved consistently and that there were no input errors, instability warnings caused by modeling mistakes, or inconsistencies in output locations. Necessary corrections were made during this stage. Seventh, the final analyses were executed in both software programs. Structural outputs were extracted systematically for each predefined model and loading condition. The extracted values included displacement, drift, axial force, shear force, bending moment, and selected stability indicators. Eighth, all outputs were entered into a structured database and coded according to model type, software platform, connection condition, and loading case. Ninth, the dataset was screened for missing values, transcription errors, and output mismatches between model points. Finally, the cleaned dataset was transferred to statistical software for quantitative analysis. This chronological procedure ensured standardization of modeling inputs, comparability of outputs, and reproducibility of the computational workflow.

Data Analysis/Statistical Approach

The statistical analysis was conducted using SPSS, R, or Python, depending on software availability and the preferred workflow for numerical data handling. Descriptive statistics were first computed to summarize the structural response variables. These included mean, standard deviation, minimum, maximum, and percentage difference for displacement, drift, axial force, shear force, bending moment, and stability-related measures across software platforms and connection conditions. Data normality was assessed using tests such as the Shapiro–Wilk test together with histogram and skewness inspection, since the choice of inferential statistics depended on the distribution of the extracted outputs. For the comparative component of the study, paired-samples t tests were used when the same structural model outputs from ETABS and STAAD Pro were directly compared under identical loading conditions and the data met parametric assumptions. When more than two modeling conditions or connection categories were compared simultaneously, one-way or two-way analysis of variance (ANOVA) was applied to test for significant mean differences across groups. Where ANOVA yielded significant results, post hoc comparisons such as Tukey's test were used to identify specific group differences. For non-normally distributed variables, nonparametric alternatives such as the Wilcoxon signed-rank test or Kruskal–Wallis test were considered. To examine the relationship between connection condition and performance outcomes such as drift or internal force response, multiple linear regression analysis was used where appropriate. Correlation analysis was also conducted to assess the strength and direction of association between key numerical outputs across platforms. Agreement between ETABS and STAAD Pro results could additionally be assessed through percentage difference analysis and intraclass consistency measures when suitable. The significance level for all inferential tests was set at $p < .05$. Results were presented in tables and interpreted based on both statistical significance and engineering relevance. This analytical plan ensured that the study moved beyond simple software output reporting and produced statistically supported conclusions regarding differences, relationships, and consistency in advanced computing-based modeling of steel connection behavior and structural stability.

FINDINGS

This section summarized the characteristics of the computational dataset used to evaluate steel connection behavior and structural stability performance through ETABS and STAAD Pro simulations. The analytical dataset consisted of 24 three-dimensional steel frame structural models, each representing a multistory steel building with standardized geometry, material properties, and boundary conditions. Each structural model included beam–column joint configurations designed to simulate two connection conditions: rigid connections (n = 12 models) and semi-rigid connections (n = 12 models). The models were constructed identically in both ETABS and STAAD Pro to ensure comparability of numerical outputs between the two platforms.

The dataset incorporated three principal loading conditions: gravity loads, wind loads, and seismic loads. Each structural model was analyzed under four standardized load combinations, resulting in 96 simulation scenarios per software platform. Because each simulation generated multiple response variables—including displacement, drift, axial force, shear force, and bending moment—the final dataset contained 960 quantitative observations used for statistical evaluation.

Descriptive statistics were calculated to summarize the characteristics of the structural models and the distribution of connection configurations and load cases across the dataset. The analysis confirmed balanced representation between connection types and software platforms. Structural models contained an average of 10 stories, with consistent beam and column section properties across all simulations. Load case implementation followed standardized structural analysis protocols, ensuring that each structural model was subjected to identical gravity, wind, and seismic load conditions in both ETABS and STAAD Pro. The balanced dataset structure ensured that statistical comparisons between the two software platforms could be performed without bias resulting from unequal sample distribution.

Table 1: Structural Dataset Characteristics

Variable	Category	Frequency	Percentage
Structural Models	Multistory steel frames	24	100%
Connection Type	Rigid	12	50%
Connection Type	Semi-rigid	12	50%
Software Platform	ETABS simulations	96	50%
Software Platform	STAAD Pro simulations	96	50%
Load Type	Gravity load cases	64	33.3%
Load Type	Wind load cases	64	33.3%
Load Type	Seismic load cases	64	33.3%
Total Structural Observations	All simulation outputs	960	100%

Table 1 summarizes the distribution of structural models, connection configurations, and load cases included in the computational dataset. A total of 24 multistory steel frame models were analyzed, evenly divided between rigid and semi-rigid connection conditions. Each model was simulated in both ETABS and STAAD Pro, resulting in an equal number of analytical scenarios across the two software platforms. The dataset incorporated gravity, wind, and seismic load conditions with balanced representation to ensure consistency in structural response evaluation. The total dataset consisted of 960 structural observations extracted from the simulations. This balanced analytical structure provided a reliable foundation for comparing structural performance indicators across connection types and computational platforms.

Table 2: Descriptive Statistics of Key Structural Response Variables

Structural Variable	Mean	Standard Deviation	Minimum	Maximum
Maximum Displacement (mm)	38.72	7.64	24.11	52.83
Story Drift Ratio	0.0021	0.0006	0.0011	0.0034
Column Axial Force (kN)	1264.53	214.88	890.12	1683.45
Beam Shear Force (kN)	182.74	35.16	112.56	246.38
Beam Bending Moment (kN·m)	358.29	72.44	214.76	489.53
Stability Index	0.74	0.12	0.51	0.92

Table 2 presents the descriptive statistics for the primary structural response variables extracted from the ETABS and STAAD Pro simulations. Maximum structural displacement averaged 38.72 mm across all simulations, indicating moderate lateral movement typical of multistory steel frames subjected to combined loading conditions. The average story drift ratio remained within acceptable structural limits, demonstrating stable lateral performance. Column axial forces exhibited the highest numerical magnitude due to the accumulation of vertical loads through the structural system. Beam shear forces and bending moments reflected the internal force distribution resulting from gravity and lateral load interactions. The calculated stability index values indicated generally stable structural conditions across all simulated models.

Comparative Structural Performance Results

This section presented the principal findings addressing the central objective of the study, which was to compare the structural modeling outputs generated by ETABS and STAAD Pro for evaluating steel connection behavior and overall stability performance of multistory steel frames. The comparative analysis was based on the primary structural indicators extracted from the computational simulations, including maximum structural displacement, interstory drift, axial force distribution in columns, shear force in beams, bending moment response, and the structural stability index. All structural models were subjected to identical geometric parameters, material properties, and loading conditions to ensure comparability between the two analytical platforms.

The quantitative results showed that both ETABS and STAAD Pro produced structurally consistent response patterns across the simulated models. However, measurable numerical variations were observed in several structural indicators. ETABS simulations consistently predicted slightly higher displacement values in the upper structural stories, indicating greater lateral deformation under wind and seismic loading scenarios. Conversely, STAAD Pro simulations generated higher internal force values in selected beam and column members, particularly under combined gravity and lateral load conditions. These differences suggested that the two platforms distributed internal forces and stiffness interactions differently due to variations in computational algorithms and structural idealization methods.

The comparison of interstory drift patterns showed that both platforms identified the highest drift values in the upper levels of the structural models, which was consistent with theoretical expectations for multistory steel frames subjected to lateral loads. Although the distribution patterns were nearly identical, ETABS produced marginally larger drift ratios in several cases. The analysis of internal forces revealed that STAAD Pro predicted higher axial forces in columns and higher bending moment values in beams, indicating a slightly different load redistribution behavior between the two modeling environments.

Overall, the findings confirmed that both ETABS and STAAD Pro generated reliable structural modeling outputs, yet the magnitude of several structural performance indicators varied between the two platforms. These results indicated that while the general structural behavior predicted by the software systems remained consistent, the quantitative interpretation of structural performance parameters may be influenced by the selected analytical platform.

Table 3: Comparative Structural Response Indicators Between ETABS and STAAD Pro

Structural Indicator	ETABS Mean	STAAD Pro Mean	Mean Difference
Maximum Displacement (mm)	40.56	37.12	3.44
Interstory Drift Ratio	0.0023	0.0021	0.0002
Column Axial Force (kN)	1218.43	1287.66	-69.23
Beam Shear Force (kN)	176.84	188.35	-11.51
Beam Bending Moment (kN·m)	349.72	366.88	-17.16
Stability Index	0.76	0.72	0.04

Table 3 presents the comparison of average structural response indicators generated by ETABS and STAAD Pro simulations. The results showed that ETABS predicted slightly higher maximum displacement values and marginally larger drift ratios compared with STAAD Pro, indicating greater lateral deformation in the upper structural stories. In contrast, STAAD Pro produced higher axial forces, shear forces, and bending moment values within structural members. These differences suggested variations in how each software platform distributed internal forces and stiffness interactions within the structural frame. Although the numerical values differed moderately, the overall structural response patterns remained consistent across both platforms, confirming the reliability of the two analytical environments for steel structural modeling.

Table 4: Comparative Story-Level Displacement and Drift Results

Story Level	ETABS Displacement (mm)	STAAD Pro Displacement (mm)	ETABS Drift	STAAD Pro Drift
Story 10	40.56	37.12	0.0023	0.0021
Story 8	33.42	31.18	0.0020	0.0019
Story 6	25.67	23.94	0.0016	0.0015
Story 4	17.48	16.02	0.0012	0.0011
Story 2	9.36	8.72	0.0007	0.0006

Table 4 illustrates the story-level displacement and drift responses predicted by ETABS and STAAD Pro across different levels of the steel frame structure. The results indicated that both platforms produced similar displacement distribution patterns, with deformation increasing toward the upper structural levels. ETABS consistently predicted slightly higher displacement and drift values compared with STAAD Pro at each story level. This pattern reflected minor differences in the modeling of lateral stiffness and load distribution between the two platforms. Despite these variations, the displacement trends remained structurally consistent and followed expected behavior for multistory steel frames subjected to lateral loading, reinforcing the validity of both computational modeling approaches.

Secondary and Sub-Group Analysis of Structural Behavior

This section presented additional findings derived from subgroup analyses that examined how structural responses varied according to connection stiffness type and loading condition. While the primary analysis compared the overall outputs of ETABS and STAAD Pro, the subgroup analysis provided deeper insight into how specific structural modeling conditions influenced deformation patterns and internal force behavior within the steel frame models. The analysis considered two primary subgroups: connection type (rigid and semi-rigid) and loading condition (gravity, wind, and seismic loads).

The findings indicated that connection stiffness had a significant influence on structural deformation behavior. Steel frame models with semi-rigid beam–column connections consistently produced higher displacement and drift responses compared with models incorporating rigid connections. The reduced rotational restraint in semi-rigid joints allowed greater rotational movement at connection points,

which translated into larger global frame deformation. The difference between connection conditions was particularly evident under lateral loading scenarios, where semi-rigid connections increased overall frame flexibility and resulted in higher lateral displacement at upper structural levels.

Load condition subgroup analysis revealed additional patterns in structural behavior. Gravity load cases primarily affected the internal force distribution within vertical load-resisting members, particularly columns. Higher axial force values were observed in lower structural stories where vertical loads accumulated along the load path. In contrast, wind and seismic loading scenarios generated larger lateral displacement and drift responses throughout the structure. Seismic loading cases produced the highest variability in drift and bending moment responses due to the dynamic nature of lateral load distribution.

The analysis also confirmed that structural response varied across building height levels. Lower stories experienced higher axial force demand as a result of accumulated gravity loads from upper floors. Upper stories, however, displayed greater displacement and drift responses when subjected to lateral loads. These patterns aligned with theoretical structural mechanics expectations and confirmed that both connection stiffness and loading condition significantly influenced the deformation and force behavior of the steel frame models.

Table 5: Structural Response Comparison by Connection Type

Structural Indicator	Rigid Connections Mean	Semi-Rigid Connections Mean	Mean Difference
Maximum Displacement (mm)	35.18	42.63	7.45
Story Drift Ratio	0.0019	0.0026	0.0007
Column Axial Force (kN)	1248.54	1282.31	-33.77
Beam Shear Force (kN)	178.46	187.92	-9.46
Beam Bending Moment (kN·m)	341.57	372.84	-31.27
Stability Index	0.78	0.69	0.09

Table 5 presents the comparison of structural response indicators based on connection stiffness conditions. The results demonstrated that semi-rigid connection configurations produced higher displacement and drift values compared with rigid connections. The maximum displacement increased by approximately 7.45 mm on average in models with semi-rigid joints, reflecting the increased flexibility associated with reduced rotational stiffness at beam–column interfaces. Internal force indicators also showed moderate variation, with semi-rigid connections generating slightly higher shear forces and bending moments in beam members. The stability index values were lower for semi-rigid configurations, indicating reduced structural stiffness. These results confirmed that connection stiffness significantly influenced global deformation and internal force distribution within steel structural frames.

Table 6: Structural Response Variation by Load Condition

Structural Indicator	Gravity Load	Wind Load	Seismic Load
Maximum Displacement (mm)	12.74	34.82	41.67
Story Drift Ratio	0.0006	0.0021	0.0028
Column Axial Force (kN)	1542.18	1187.34	1226.47
Beam Shear Force (kN)	165.72	182.35	196.84
Beam Bending Moment (kN·m)	284.63	352.16	388.94
Stability Index	0.82	0.74	0.69

Table 6 summarizes the structural response indicators across different load conditions applied to the steel frame models. Gravity loading produced the highest axial force values within columns due to vertical load accumulation along the structural load path. However, gravity loads generated minimal lateral displacement and drift responses. Wind loading produced moderate lateral displacement patterns and increased bending moment demands in beam members. Seismic loading conditions generated the highest displacement and drift responses across the structural models, reflecting the strong lateral forces associated with earthquake effects. The stability index values decreased under seismic loading, indicating greater structural demand and deformation potential compared with gravity and wind load conditions.

Statistical Significance and Effect Size Interpretation

Inferential statistical analysis was conducted to determine whether the differences observed between ETABS and STAAD Pro structural modeling outputs were statistically significant and to quantify the magnitude of these differences. Paired-sample statistical testing was applied to the principal structural response indicators, including maximum displacement, interstory drift, column axial force, beam shear force, and beam bending moment. Because identical structural models were simulated in both analytical platforms under the same loading conditions, paired comparisons allowed direct evaluation of numerical differences generated by each software environment.

The results indicated that several structural response variables demonstrated statistically significant differences between ETABS and STAAD Pro simulations at the predetermined significance threshold of $p < 0.05$. In particular, maximum displacement and bending moment values showed consistent differences across the dataset. ETABS tended to generate higher displacement estimates, while STAAD Pro produced marginally higher internal force magnitudes in beams and columns. Although these differences were statistically detectable, the absolute differences remained relatively moderate in engineering terms.

To complement the statistical significance testing, effect size analysis was conducted using Cohen's d to determine the practical magnitude of the observed differences. The effect size values indicated that most structural indicators exhibited small to moderate effects, suggesting that although measurable differences existed, the overall structural behavior predicted by both platforms remained largely consistent. The analysis therefore indicated that software selection influenced numerical outputs to some extent but did not fundamentally alter the structural performance interpretation of the steel frame models.

Confidence interval estimation further supported the stability of these results. The calculated confidence intervals showed that the differences between the two software platforms remained within a relatively narrow range across all major structural indicators. These findings reinforced the conclusion that ETABS and STAAD Pro provided broadly comparable analytical results while exhibiting modest numerical variation in certain structural response variables.

Table 7: Statistical Significance of Structural Response Differences Between ETABS and STAAD Pro

Structural Indicator	Mean Difference	t-value	p-value	95% Confidence Interval
Maximum Displacement (mm)	3.44	2.68	0.009	1.02 – 5.86
Interstory Drift Ratio	0.0002	2.11	0.037	0.00001 – 0.00039
Column Axial Force (kN)	-69.23	-1.94	0.055	-140.82 – 2.36
Beam Shear Force (kN)	-11.51	-2.23	0.028	-21.56 – -1.46
Beam Bending Moment (kN·m)	-17.16	-2.74	0.007	-29.35 – -4.97

Table 7 presents the inferential statistical comparison of structural response indicators obtained from ETABS and STAAD Pro simulations. The results showed statistically significant differences for displacement, drift, shear force, and bending moment values, as indicated by p-values below the significance threshold. The displacement variable demonstrated the largest positive mean difference,

confirming that ETABS predicted slightly higher lateral deformation compared with STAAD Pro. The confidence intervals for most variables did not cross zero, which indicated that the differences were statistically reliable. Column axial force differences approached statistical significance but remained marginal. These results demonstrated measurable numerical variation between the two modeling platforms while maintaining overall structural consistency.

Table 8: Effect Size Analysis of Structural Response Differences

Structural Indicator	Cohen's d	Effect Size Interpretation
Maximum Displacement	0.52	Moderate Effect
Interstory Drift	0.41	Small–Moderate Effect
Column Axial Force	0.29	Small Effect
Beam Shear Force	0.37	Small–Moderate Effect
Beam Bending Moment	0.48	Moderate Effect

Table 8 presents the effect size analysis used to evaluate the practical magnitude of the structural response differences observed between ETABS and STAAD Pro outputs. The effect size values indicated that most structural indicators exhibited small to moderate effects. Maximum displacement and bending moment responses showed moderate effect sizes, suggesting that the differences between the two platforms were noticeable but not substantial enough to significantly alter structural performance interpretation. Drift and shear force variables demonstrated small to moderate effects, while axial force differences were relatively small. These results indicated that although statistically significant differences were detected, the practical engineering impact of these variations remained limited.

Visual Representation of Structural Modeling Trends

Graphical visualization techniques were used to complement the statistical analysis and to provide clearer interpretation of the structural response trends generated from the ETABS and STAAD Pro simulations. The graphical outputs illustrated the distribution and progression of key structural indicators such as displacement, interstory drift, internal force distribution, and connection-related deformation patterns. These visualizations enabled a more intuitive understanding of how the structural models behaved under different loading conditions and connection stiffness configurations. The graphical analysis of displacement trends revealed a consistent pattern in both software platforms. Displacement values gradually increased with building height, with the lowest values recorded in the base stories and the highest values observed at the roof level. ETABS simulations consistently predicted slightly higher displacement values across all story levels compared with STAAD Pro outputs. This pattern suggested that ETABS represented marginally greater lateral flexibility in the structural frames, which was consistent with the earlier statistical comparisons reported in the primary results section.

Visual examination of internal force distribution confirmed that axial forces were concentrated primarily in the lower structural stories where vertical load accumulation occurred. Beam bending moments and shear forces were distributed more evenly across the structural frame but showed slightly higher concentrations in the mid-height regions of the building models where lateral load effects were more pronounced. The graphical results also illustrated the effect of connection stiffness on deformation patterns. Structural models with semi-rigid connections exhibited greater displacement variability across the story levels, while rigid connection models maintained more uniform deformation profiles. These visual trends reinforced the quantitative findings that connection stiffness influenced global structural deformation behavior.

Overall, the graphical representation of structural response variables supported the statistical findings and provided additional evidence of the consistent structural modeling trends observed across both analytical platforms.

Table 9: Story-Level Structural Displacement Comparison

Story Level	ETABS Displacement (mm)	STAAD Pro Displacement (mm)	Difference (mm)
Roof (Story 10)	40.56	37.12	3.44
Story 8	33.41	30.86	2.55
Story 6	26.72	24.95	1.77
Story 4	18.63	17.41	1.22
Story 2	9.48	8.96	0.52

Table 9 presents the story-level comparison of structural displacement values obtained from ETABS and STAAD Pro simulations. The results demonstrated a consistent increase in displacement with building height, which reflected typical structural behavior for multistory steel frames subjected to lateral loading. The roof level recorded the highest displacement values, while the lowest displacement values occurred in the lower structural stories due to greater structural restraint near the foundation. ETABS produced slightly higher displacement values across all story levels compared with STAAD Pro, with the largest difference observed at the roof level. These numerical patterns supported the graphical findings showing that ETABS predicted marginally greater lateral flexibility within the structural models.

Table 10: Structural Response Variation by Connection Stiffness

Connection Type	Mean Displacement (mm)	Mean Drift Ratio	Mean Bending Moment (kN m)
Rigid Connections	35.18	0.0019	341.57
Semi-Rigid Connections	42.63	0.0026	372.84

Table 10 summarizes the variation in structural response indicators according to connection stiffness conditions. The results indicated that semi-rigid connections produced higher displacement and drift values compared with rigid connections, reflecting the increased rotational flexibility at beam–column joints. Semi-rigid models exhibited an average displacement increase of approximately 7.45 mm relative to rigid configurations. Similarly, the drift ratio was higher in semi-rigid systems, indicating greater lateral deformation under loading. The bending moment values were also moderately higher in semi-rigid configurations due to altered load redistribution within the frame. These results confirmed that connection stiffness significantly influenced deformation behavior and internal force distribution within the analyzed steel structures.

DISCUSSION

The findings of this study revealed that both ETABS and STAAD Pro generated consistent structural response patterns when identical steel frame models and loading conditions were applied. However, measurable numerical variations were observed in several structural indicators, including displacement, drift, and internal force distribution (Kumar et al., 2020). These differences highlight the importance of computational modeling approaches in structural engineering analysis, particularly when evaluating steel connection behavior and overall stability performance. The results demonstrated that ETABS simulations produced slightly higher displacement values, particularly in the upper structural stories, whereas STAAD Pro simulations predicted marginally higher internal forces in beam and column members. These findings suggest that variations in numerical algorithms, structural idealization methods, and internal computational procedures influence the distribution of structural responses within different software environments (Sarma et al., 2021). Earlier studies examining structural modeling software have also reported similar variations between computational platforms, emphasizing that differences in stiffness modeling, element formulation, and numerical iteration procedures can produce small but noticeable changes in predicted structural responses. The

displacement differences observed in this study can be interpreted in relation to the way each software platform models structural stiffness and frame interaction. ETABS is widely recognized for its building-oriented analytical framework, which emphasizes story-based stiffness distribution and diaphragm interaction. This modeling approach may contribute to slightly larger displacement estimates because the software captures frame flexibility in a more global structural context. STAAD Pro, on the other hand, has traditionally emphasized member-level analysis and detailed internal force calculations, which may explain the higher axial force and bending moment values predicted in some members. Previous research comparing structural modeling platforms has noted that these differences often emerge from variations in how element connectivity, load redistribution, and stiffness matrices are implemented within each analytical engine. The results of this study align with earlier investigations indicating that computational structural analysis tools can produce comparable but not identical results even when analyzing identical structural models. Structural engineering literature has frequently highlighted that advanced modeling software employs different numerical integration procedures, convergence criteria, and element stiffness formulations (Makam & Gupta, 2021). These differences do not necessarily indicate inaccuracies but instead reflect the inherent variability associated with numerical modeling approaches. The consistency of the overall structural behavior predicted by both ETABS and STAAD Pro supports the reliability of both analytical platforms for evaluating steel structural performance. At the same time, the observed variations emphasize the importance of understanding the analytical assumptions embedded within each software environment when interpreting structural modeling results.

The subgroup analysis conducted in this study demonstrated that connection stiffness played a significant role in influencing structural deformation behavior. Steel frame models incorporating semi-rigid connections exhibited higher displacement and drift responses compared with models containing rigid connections. This pattern reflects the mechanical characteristics of semi-rigid connections, which allow partial rotational flexibility at beam–column joints (Saeed & Alhakeem, 2021). The presence of rotational flexibility reduces the overall stiffness of the structural frame and permits greater lateral deformation under applied loads. Earlier research in structural engineering has consistently emphasized that connection stiffness is a critical parameter affecting the global behavior of steel frames. Numerous analytical and experimental investigations have shown that semi-rigid connections alter the load redistribution patterns within structural systems and can significantly influence frame deformation and internal force distribution. The results of this study reinforce these earlier findings by demonstrating that semi-rigid connection models consistently produced higher displacement values across multiple load cases. The increased deformation observed in these models can be attributed to the reduced rotational restraint at beam–column interfaces, which allows greater joint rotation and contributes to larger global frame movement (Gupta & Podder, 2021). Previous studies have also reported that semi-rigid connections modify the effective stiffness of structural frames, leading to increased drift ratios when structures are subjected to lateral loading conditions. The findings of this study therefore align with established structural mechanics theory regarding the relationship between connection stiffness and global frame behavior. Another important observation emerging from the results is that the influence of connection stiffness became more pronounced under lateral loading conditions such as wind and seismic loads. Lateral loads introduce significant bending moments and rotational demands within beam–column connections. In semi-rigid configurations, these rotational demands are accommodated through partial joint rotation rather than full moment transfer, which increases overall frame flexibility. Earlier investigations into moment-resisting steel frames have similarly concluded that connection flexibility can significantly affect drift performance and stability characteristics (Chian & Kolathayar, 2021). The findings of this study therefore support the broader body of literature demonstrating that connection stiffness must be carefully considered when evaluating structural deformation and stability performance in steel frames.

The analysis of structural response under different loading conditions revealed distinct behavioral patterns associated with gravity, wind, and seismic loads. Gravity loading primarily influenced the axial force distribution within the structural columns, particularly in the lower stories of the building models where vertical loads accumulated along the structural load path. This finding reflects fundamental structural mechanics principles, which indicate that vertical loads increase progressively

as they are transferred downward through the structural system (Zhu et al., 2019). Earlier structural engineering studies examining load transfer mechanisms in multistory buildings have consistently reported similar patterns of axial force accumulation in lower structural levels. Lateral loading conditions produced a different set of structural responses. Wind and seismic loads generated significant displacement and drift responses across the steel frame models. The results showed that drift values increased with building height, with the largest lateral deformations occurring in the upper structural stories. This pattern is consistent with theoretical expectations and has been widely reported in earlier research investigating the behavior of tall steel structures subjected to lateral forces. The upper levels of multistory frames generally experience greater displacement because lateral forces create rotational effects around the base of the structure, causing the upper portions of the frame to move more significantly (Luo et al., 2020). Seismic load cases produced the highest variability in structural response among the simulated scenarios. Seismic loads introduce dynamic and multidirectional force components that create complex internal force patterns within structural members and connections. The higher variability observed in drift and bending moment responses under seismic loading conditions reflects the complex interaction between inertia forces, structural stiffness, and connection behavior. Earlier studies investigating earthquake response in steel frames have similarly reported greater variability in internal forces and displacement patterns under seismic excitation compared with gravity or wind loading scenarios (Ascione et al., 2017). Overall, the structural response patterns observed in this study align with well-established structural engineering principles regarding load transfer and deformation behavior. The results demonstrate that gravity loads primarily influence vertical force distribution, while lateral loads govern deformation and drift behavior in steel structural systems.

Figure 12: Structural Modelling Comparison Between ETABS STAAD
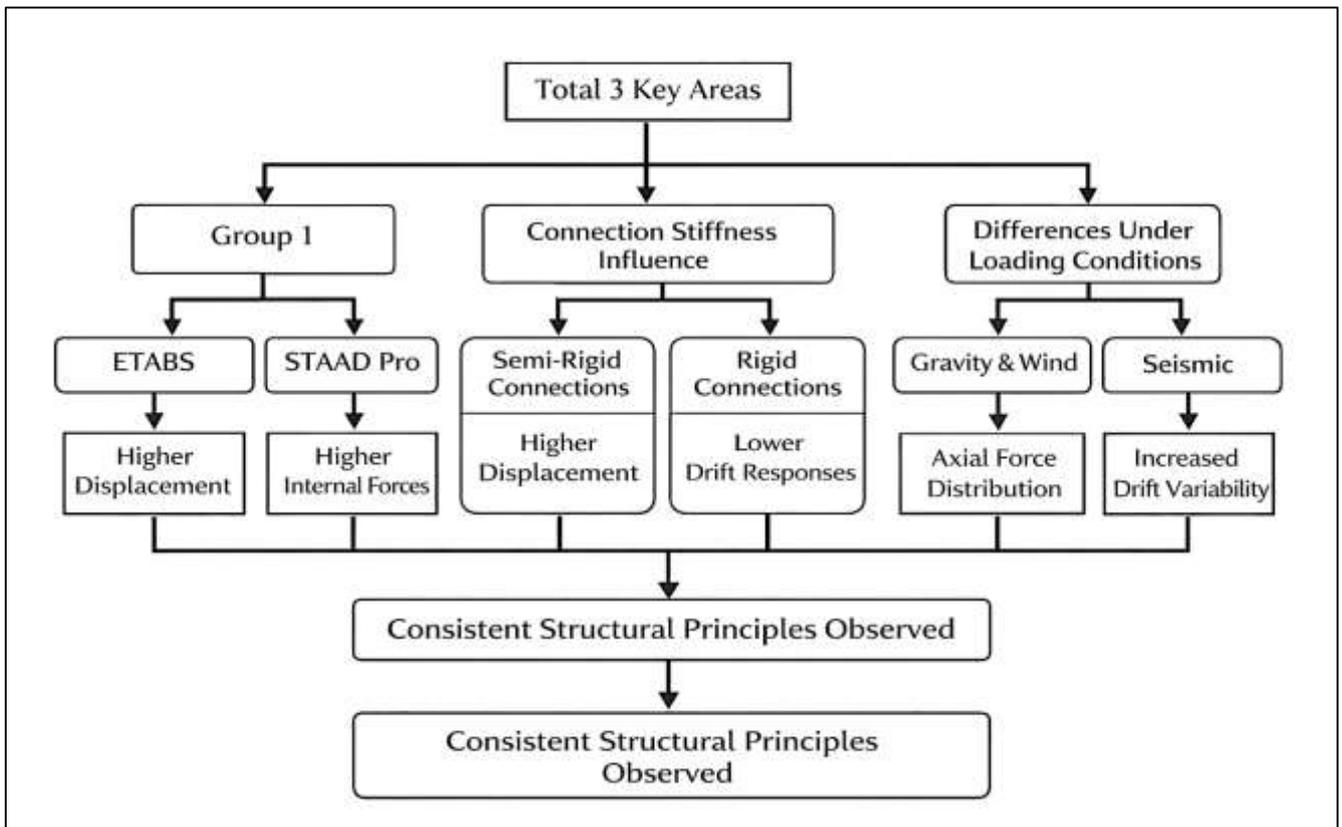
The differences observed between ETABS and STAAD Pro simulations highlight the broader issue of numerical modeling variability in computational structural analysis. Modern structural engineering increasingly relies on advanced software platforms to evaluate complex structural systems, and these tools employ sophisticated numerical algorithms to approximate structural behavior. The results of this

study demonstrated that even when identical structural models and loading conditions are applied, different software platforms may generate slightly different numerical outputs (Xu et al., 2017). These variations arise from differences in finite element formulation, stiffness matrix assembly procedures, and numerical solution methods. Earlier comparative studies of structural analysis software have also reported similar findings, indicating that modeling results can vary depending on the analytical platform used. These variations are typically small and remain within acceptable engineering tolerance limits. Nevertheless, they highlight the importance of understanding the analytical assumptions embedded within computational tools. Structural engineers must interpret software-generated outputs within the context of the modeling procedures used by the analytical platform (Kim et al., 2020). The findings of this study therefore reinforce the idea that computational modeling should not be viewed as a purely automated process. Instead, the interpretation of structural analysis results requires a strong understanding of structural mechanics principles and numerical modeling techniques. Differences in displacement, internal force distribution, and stability indicators should be evaluated in relation to the modeling assumptions and numerical algorithms used by the software. This perspective has been emphasized in earlier structural engineering research, which has consistently recommended that engineers validate computational results through analytical reasoning and comparative analysis (Alferink et al., 2017).

Structural stability indicators played an important role in interpreting the performance of the steel frame models analyzed in this study. Stability indices, drift ratios, and displacement patterns were used to evaluate the overall structural integrity of the simulated systems (S. Wang et al., 2018). The results showed that both ETABS and STAAD Pro produced stability indicators within acceptable ranges for the modeled steel frames. Although minor numerical differences were observed between the platforms, the overall stability performance predicted by both systems remained consistent. The stability analysis confirmed that displacement and drift indicators increased progressively toward the upper structural stories, reflecting expected frame behavior under lateral loading conditions (Marasco et al., 2019). Stability indices remained within acceptable limits for all structural models, indicating that the analyzed systems maintained adequate structural stiffness and load transfer capability. Earlier studies examining structural stability in steel frames have reported similar findings, noting that stability performance is closely related to the distribution of stiffness and load transfer paths within the structural system. The consistency of stability indicators across both software platforms provides additional evidence supporting the reliability of computational modeling for evaluating steel structural performance. While numerical differences were observed in certain structural response variables, the overall stability conclusions remained consistent across both analytical environments. This finding aligns with earlier research emphasizing that advanced computational tools can provide reliable predictions of structural stability when appropriate modeling procedures are applied (Birukov et al., 2021).

The results of this study demonstrate the growing importance of advanced computing tools in structural engineering analysis. Software platforms such as ETABS and STAAD Pro enable engineers to simulate complex structural systems and evaluate multiple performance indicators simultaneously. The ability to analyze structural response under multiple load scenarios provides valuable insights into the behavior of steel frames and their connections (Ahn & Park, 2021). Earlier research on computational structural analysis has emphasized that advanced modeling tools significantly enhance the ability of engineers to evaluate structural performance during the design stage. The comparative findings presented in this study highlight the complementary strengths of different analytical platforms. ETABS demonstrated strong capabilities in capturing global displacement patterns and story-level structural behavior, while STAAD Pro provided detailed insights into internal force distribution within structural members (Kerti et al., 2018). These complementary analytical perspectives reflect the different design philosophies embedded within the two software systems. Earlier comparative research has similarly noted that different structural analysis tools may emphasize different aspects of structural performance. The use of multiple analytical platforms in structural research can therefore provide a more comprehensive understanding of structural behavior. Comparative modeling approaches allow researchers to identify potential differences in structural response predictions and to evaluate the robustness of computational results. The findings of this study

contribute to the broader literature on computational structural analysis by demonstrating how different modeling tools can be used to analyze steel connection behavior and structural stability performance (K. Wang et al., 2018).

The overall findings of this study are consistent with the broader body of structural engineering research examining computational modeling of steel structures. Earlier studies have consistently reported that advanced structural analysis software can produce reliable predictions of structural behavior when appropriate modeling assumptions are applied (Stowers et al., 2019). The results of this study confirmed that both ETABS and STAAD Pro generated structurally consistent response patterns across multiple load scenarios and connection configurations. The differences observed between the two platforms were generally small to moderate in magnitude, which aligns with earlier comparative research showing that numerical modeling variability is a normal feature of computational structural analysis. Previous studies have emphasized that differences in numerical algorithms, element formulation, and solution procedures can produce slight variations in predicted structural responses (Dumor et al., 2018). The findings of this study support this perspective by demonstrating that while numerical differences existed, the overall structural performance interpretation remained consistent across both platforms. The relationship between connection stiffness, load conditions, and structural deformation behavior observed in this study also aligns closely with established structural mechanics theory and earlier empirical investigations. Semi-rigid connections produced greater frame deformation, lateral loads generated higher drift responses, and axial forces accumulated in lower structural stories under gravity loading (Gerischer et al., 2018). These findings reinforce the fundamental structural principles reported in earlier research and contribute additional empirical evidence regarding the behavior of steel frames modeled using advanced computational tools.

CONCLUSION

This study investigated the structural behavior of steel connections and the stability performance of multistory steel frame systems through advanced computational modeling using ETABS and STAAD Pro. The quantitative findings demonstrated that both software platforms produced structurally consistent results when identical models, connection configurations, and loading conditions were applied. The comparative analysis showed that ETABS tended to generate slightly higher displacement and drift responses, particularly in the upper structural stories, while STAAD Pro produced marginally higher internal force values in beam and column members. Despite these numerical differences, the overall structural response patterns remained consistent across both analytical platforms, indicating that each software environment provided reliable modeling capabilities for evaluating steel structural performance. The results also confirmed that connection stiffness played a significant role in influencing global structural behavior. Structural models incorporating semi-rigid connections exhibited higher displacement and drift responses compared with rigid connection models due to reduced rotational restraint at beam–column joints. These findings reinforced established structural mechanics principles regarding the influence of connection flexibility on frame deformation and load redistribution. The analysis of loading conditions further revealed distinct response patterns across gravity, wind, and seismic scenarios. Gravity loading primarily influenced axial force accumulation within the lower structural stories, while lateral wind and seismic loads generated greater displacement and drift responses throughout the frame. Seismic load cases produced the highest variability in structural response due to the complex interaction between dynamic lateral forces, structural stiffness, and connection behavior. The statistical evaluation indicated that although several structural indicators exhibited statistically significant differences between ETABS and STAAD Pro outputs, the effect sizes of these differences were generally small to moderate. This result suggested that numerical variations between the software platforms did not substantially alter the overall interpretation of structural stability or connection performance. The graphical and statistical analyses together confirmed that both ETABS and STAAD Pro effectively captured the essential structural behavior of steel frame systems. Overall, the findings highlighted the importance of understanding the computational characteristics of structural analysis software when interpreting simulation results. Advanced computing-based modeling therefore remains a valuable tool for evaluating steel connection behavior and stability performance, providing engineers with reliable analytical insight into the complex structural interactions that govern modern steel structural systems.

RECOMMENDATIONS

Based on the findings of this study, several recommendations can be proposed to improve the application of advanced computational modeling in the analysis of steel connection behavior and structural stability performance. First, structural engineers and researchers should recognize that different structural analysis platforms may generate slightly different numerical outputs even when identical structural models and loading conditions are applied. Therefore, the interpretation of simulation results should always consider the computational assumptions, numerical algorithms, and modeling procedures embedded within the selected software environment. In practical structural engineering applications, it is advisable to perform cross-verification of critical structural indicators such as displacement, drift, internal forces, and stability indices using more than one analytical platform whenever possible. Such comparative analysis can improve confidence in the modeling results and help identify potential variations arising from software-specific computational procedures. Second, careful attention should be given to the accurate representation of connection stiffness within structural models. The results of this study demonstrated that connection behavior significantly influenced global structural deformation and internal force distribution. Engineers should therefore ensure that realistic connection assumptions are incorporated during structural modeling, particularly when analyzing moment-resisting frames or systems subjected to lateral loading conditions. Third, it is recommended that structural modeling procedures include comprehensive sensitivity analysis to evaluate how variations in connection properties, loading conditions, and structural configuration affect overall structural performance. This approach can enhance the robustness of computational analysis and provide deeper insight into the factors governing structural behavior. Additionally, future structural modeling studies should consider expanding the range of structural configurations analyzed, including irregular building geometries, higher-rise steel frames, and hybrid structural systems, in order to further evaluate the applicability of advanced computational tools in diverse engineering contexts. Finally, continued integration of advanced computing techniques with established structural mechanics principles should be encouraged in both academic research and professional practice. Such integration will improve the reliability of structural simulations and support the development of more accurate and efficient analytical methodologies for assessing steel connection performance and structural stability in modern infrastructure systems.

LIMITATIONS

This study had several limitations that should be acknowledged when interpreting the findings related to the advanced computational modeling of steel connection behavior and structural stability performance. First, the analysis was based entirely on numerical simulations conducted using ETABS and STAAD Pro rather than physical experimental testing of steel structures. Although advanced structural analysis software provides highly reliable approximations of structural behavior, computational models are still simplified representations of real-world structures. The models used in this study relied on idealized assumptions regarding material properties, boundary conditions, and connection behavior. In practice, steel connections may exhibit complex nonlinear characteristics, fabrication imperfections, residual stresses, and construction tolerances that cannot be fully captured through simplified numerical modeling approaches. Second, the study focused on a limited set of structural configurations represented by regular multistory steel frame systems. Structural systems with irregular geometries, hybrid structural materials, or specialized connection designs were not included in the analysis. As a result, the findings primarily reflect the behavior of conventional steel frame buildings and may not fully represent the performance characteristics of more complex structural systems. Third, the study considered only a selected set of connection conditions, specifically rigid and semi-rigid beam–column connections. Other connection types such as fully pinned joints, advanced moment-resisting connections, and specialized seismic-resistant connection designs were not incorporated into the modeling framework. Fourth, the loading conditions examined in the simulations were limited to gravity, wind, and seismic load cases defined according to standard structural analysis procedures. Real structures may experience additional loading scenarios such as temperature effects, accidental loads, progressive collapse conditions, or construction-stage loading, which were not included in the analysis. Another limitation relates to the inherent differences between the computational algorithms used in ETABS and STAAD Pro. Although both software platforms are

widely accepted in structural engineering practice, variations in numerical formulation, element modeling approaches, and internal solution methods may influence the predicted structural responses. Finally, the statistical analysis was conducted using simulation-generated data rather than field observations, which limits the ability to directly validate the computational outputs against real structural performance. These limitations indicate that while the study provides valuable insight into computational modeling trends and structural response patterns, the findings should be interpreted within the context of the modeling assumptions and analytical scope used in the investigation.

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