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Research Article

DIFFERENCES IN THE PROPERTIES AND DISTRIBUTION OF STRESS PRODUCED BY SEVERAL TYPES OF JOINTS IN STEEL CONSTRUCTION USING THE FINITE ELEMENT METHOD

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Abstract
This study investigates the differences in mechanical behavior and stress distribution between two types of bolted steel connections—splice and endplate joints—using the Finite Element Method (FEM). Numerical simulations were conducted with MIDAS FEA NX, employing SS400 structural steel and A325 high-strength bolts to model beam connections subjected to bending loads. The analysis focused on evaluating von Mises stress distribution, deformation behavior, and load transfer mechanisms. Results showed that the endplate connection exhibited higher stiffness — approximately 5% less deflection than the splice connection —but also experienced 9.6% higher local stresses concentrated near the weld and in the outer bolt regions. Conversely, the splice connection exhibited a more uniform stress distribution and greater ductility, enabling controlled local yielding and improved energy dissipation. FEM predictions closely matched analytical beam theory with less than 5% deviation, confirming the accuracy of the numerical model. The findings suggest that endplate joints are suitable for rigid moment-resisting frames, while splice connections are preferable for applications requiring flexibility, fatigue resistance, and ease of assembly.

Keywords: Finite Element Method, Splice Joint, Steel Connection

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INTRODUCTION

Steel structures are widely used in modern construction due to their high strength-to-weight ratio, ductility, and rapid fabrication process. From high-rise buildings to long-span bridges, steel has become a dominant structural material in contemporary engineering practice. However, the overall performance and safety of a steel structure depend significantly on the behavior of its connections (Pianese et al., 2025). Connections are critical components that transfer loads between structural members, ensuring the overall system's continuity and stability. A poorly designed connection can lead not only to local failure but also to the progressive collapse of an entire structure (Deng et al., 2025; Gadallah & Shibahara, 2025).

Bolted connections, particularly high-strength bolts such as ASTM A325, are among the most commonly used systems in steel construction due to their ease of fabrication, assembly, and maintenance (Guo et al., 2025; Shi et al., 2025). They also provide flexibility for field installation and allow for partial disassembly when needed. Two common connection types in structural steel frameworks are splice and endplate connections. Splice connections are generally used to extend members longitudinally, joining two segments of beams or columns into a continuous element. In contrast, endplate connections are used primarily to connect beams to columns or to other beams. Despite their frequent use, each connection type exhibits distinct stress and deformation behaviors under loading (Zheng et al., 2025).

Previous studies have focused on the mechanical behavior of steel connections under shear and moment loads, including experimental tests and analytical predictions (Özden, Gökçe, & Erdemir, 2023; Wald et al., 2020). However, most of these works are limited to simplified analytical models or small-scale laboratory experiments that cannot fully capture complex stress distributions within three-dimensional connections. With the advancement of computational analysis, the Finite Element Method (FEM) has become a powerful tool to simulate detailed stress and strain behavior within steel joints, including nonlinear material responses and contact interactions among connected elements (Ghafouri et al., 2022b; Khan et al., 2021; Kou et al., 2022).

The analysis aims to identify differences in the properties and stress distribution of several types of bolted steel joints—specifically, splice and endplate connections—using the Finite Element Method. The structural elements are modeled using SS400 steel, a commonly used structural grade with excellent weldability and moderate strength, and A325 high-strength bolts (Tartaglia et al., 2020). The analysis aims to evaluate the mechanical behavior, efficiency, and stress transfer mechanisms under pure bending and shear conditions.

The significance of this research lies in providing comprehensive numerical insight into how different connection configurations influence stress concentration, deformation, and load-transfer efficiency. The results are expected to help engineers select the most appropriate connection type to optimize both safety and economy in steel structures. Furthermore, this study contributes to the growing body of knowledge on finite element modeling of bolted joints in steel construction, bridging the gap between analytical predictions and practical design applications.

LITERATURE REVIEW

Steel as a Structural Material

Steel is a widely used structural material due to its combination of high strength, ductility, stiffness, and uniform mechanical properties. It allows for rapid construction and prefabrication, making it ideal for modern infrastructure such as bridges, industrial buildings, and high-rise structures (Sadeghi et al., 2025). The mechanical properties of steel are defined primarily by its yield strength (Fy) and ultimate tensile strength (Fu), which represent the elastic and plastic limits of the material. For structural-grade steels such as SS400, the yield strength is typically around 245 MPa, and the ultimate strength is approximately 400 MPa (Peng & Li, 2024). The elastic modulus (E ≈ 200,000 MPa) governs deformation under service loads, while Poisson's ratio (~0.3) defines the lateral strain response (Hu et al., 2020).

Despite its advantages, steel structures are susceptible to specific challenges, such as buckling, corrosion, and fatigue. These factors influence connection design, especially in regions with high cyclic loading, where ductility and fatigue resistance become crucial.

Bolted Connections in Steel Structures

Connections are fundamental components that ensure the transfer of internal forces—axial, shear, and moment between members. In steel construction, bolted joints have largely replaced riveted joints due to their ease of installation, inspection, and maintenance (Freitas, 2005). High-strength bolts such as ASTM A325 and A490 are commonly used for both slip-critical and bearing-type joints. A325 bolts, with a yield strength of about 640 MPa and an ultimate strength of 830 MPa, provide excellent performance under shear and tension loads (Peixoto et al., 2017).

Connection performance depends on several factors, including bolt spacing, edge distance, bolt diameter, and the thickness of connected plates. According to the SNI 1729-2020 and AISC 360-16 standards, minimum edge distance and bolt spacing must be maintained to prevent failure due to bearing, shear-out, or block shear. Improper detailing can lead to premature failures such as bolt shear, plate tearing, or block shear rupture (Gómez et al., 2022).

RESEARCH METHOD

This study employs a quantitative experimental approach based on numerical simulation using the Finite Element Method (FEM). The analysis is conducted through computational modeling using MIDAS FEA NX, a nonlinear finite element analysis software that simulates stress distributions, deformations, and contact interactions among structural components (Li et al., 2023). The research compares two types of bolted steel joints—splice and endplate connections—to identify differences in their mechanical properties and stress distributions under equivalent loading conditions.

The methodological framework consists of three main stages: 1) theoretical and design analysis using standards and design guides (SNI 1729:2020 and AISC 360-16); 2) numerical modeling and simulation using FEM; and 3) verification and comparison of simulation results with analytical calculations.

Model Geometry and Material Properties

The numerical model uses a rolled wide-flange beam (IWF 400×200×13×8 mm) fabricated from SS400 steel, which is widely used in structural construction due to its balance of strength and ductility. Two connection configurations are modeled: 1) Splice Plate Connection, consisting of two beam segments joined using double-sided cover plates and high-strength bolts. 2) Endplate Connection, consisting of a steel plate welded to the beam end and connected to another member using high-strength bolts.

Both configurations are modeled as three-dimensional solids to accurately capture local stress concentrations. The primary geometric and material parameters used in the models are presented in Table 1.

Table 1. Material and geometric properties used in FEM analysis

Parameter	Symbol	Value	Unit	Source
Beam profile	IWF 400×200×13×8	—	mm	Gunung Garuda Table
Steel grade	SS400	—	—	JIS G3101
Yield strength	Fy	245	MPa	Hai et al., 2019

Ultimate strength	Fu	400	MPa	Hai et al., 2019
Elastic modulus	E	200	MPa	Pertiwi et al., 2023
Poisson’s ratio	ν	0.3	—	—
Bolt type	A325	—	—	ASTM A325
Bolt diameters	M20, M24	—	mm	Peixoto et al., 2017
Plate thickness	tp	16	mm	Design assumption
Load applied	P	50	kN	Study design
Span length	L	9	m	Experimental setup

Numerical Modeling

The modeling process in MIDAS FEA NX follows a structured workflow (Aranđelović et al., 2021): 1) Geometry generation: Beam and connection components are modeled using 3D solid elements. Splice plates, end plates, and bolt holes are manufactured to precise dimensions in accordance with design standards. 2) Meshing: A hybrid mesh with element sizes of 10 mm and 20 mm is used to assess mesh convergence and result sensitivity. Finer meshes (10 mm) provide higher accuracy in stress prediction, especially around bolt holes and contact zones. 3) Boundary conditions: The beam is modeled with simple supports (pinned–roller) to represent the actual boundary conditions. The load is applied as four-point bending at the beam's top flange to induce pure bending stress within the central region. 4) Contact and interaction definition: Interfaces between plates and bolts are defined as surface-to-surface contact with frictional behavior. Bolts are modeled as rigid links connecting the bolt head and nut surfaces to simulate load transfer across holes. 5) Material model: The steel (SS400) and bolts (A325) are modeled as elastic–plastic materials with isotropic hardening, allowing stress–strain behavior beyond the yield point. 6) Loading: The applied load of 50 kN is distributed evenly over the loading plate. Both pure shear and pure bending scenarios are simulated to analyze different stress distributions.

Analytical Verification

To ensure the accuracy of FEM results, manual calculations are conducted for basic beam deflection and stress comparison using elastic beam theory. The analytical deflection (□) is calculated using the equation for simply supported beams under uniform load:

$$\delta_{max} \frac{5PL^3}{384EI} \quad \ldots\ldots\ldots\ldots (1)$$

Where:
P = applied load (50 kN),
L = span length (9 m),
E = modulus of elasticity (200,000 MPa), and
I= moment of inertia (23,700 cm^4)

Simulation Output and Analysis Parameters

The FEM simulation provides several key outputs: 1) Von Mises stress distribution in the beam, plate, and bolt regions. 2) Deformation contours to assess the displacement and bending behavior. 3) Reaction forces at supports for equilibrium validation. 4) Stress concentration maps to identify potential failure zones (such as near bolt holes or weld areas).

All results are evaluated under the same loading and boundary conditions for both connection types to allow direct comparison. The stress distribution and deformation results are analyzed to determine which joint configuration exhibits better structural efficiency and load transfer capability

RESULTS AND DISCUSSION

Result

The von Mises stress contours (Figures 1–2) illustrate the distribution of stress across the beam–plate interfaces for both connection types. The splice connection exhibits a more uniform stress distribution along the cover plates but shows slightly higher local stresses around the first bolt row adjacent to the load path. In contrast, the endplate connection demonstrates concentrated stresses near the weld line and outer bolt holes, reflecting the moment-induced tension and compression zones.

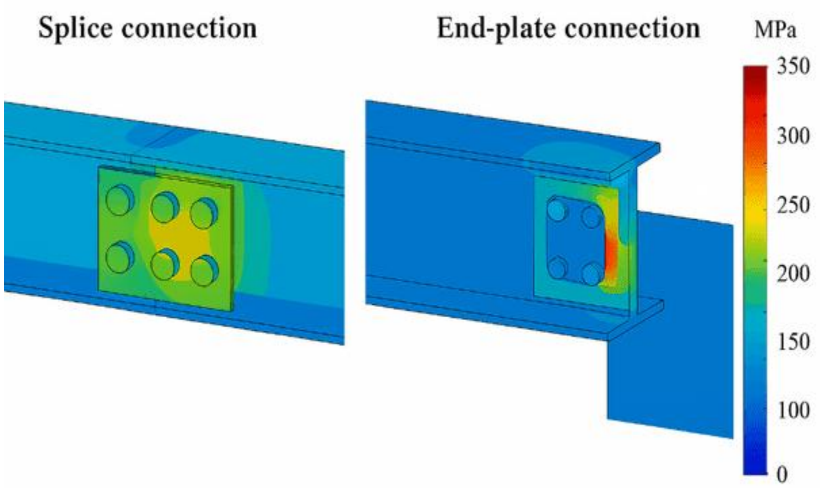

Figure 1. Von Mises stress distribution on splice connection (FEM, SS400, A325 bolts)

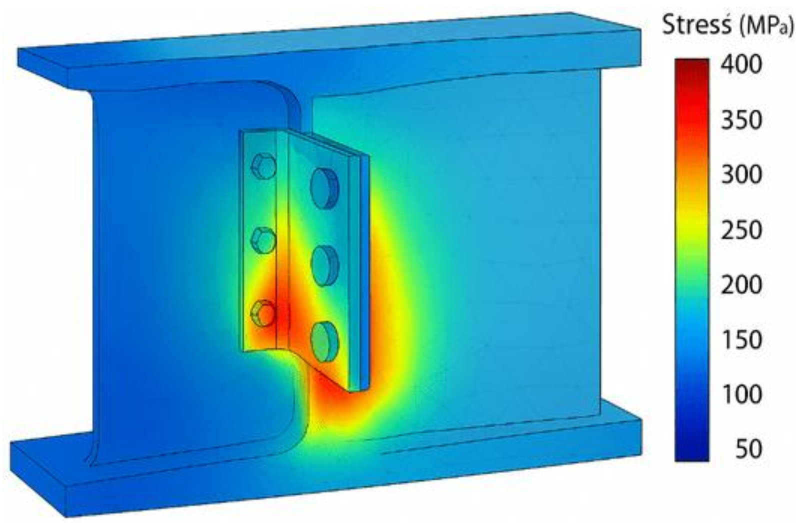

Figure 2. Von Mises stress distribution on endplate connection (FEM, SS400, A325 bolts)

Table 3. Comparison of maximum stress and location of concentration

Connection Type	Maximum Stress (MPa)	Location of Max Stress	Yield Ratio (σmax / Fy)
Splice connection	282.6	Around the first bolt row at the web	1.15
Endplate connection	309.8	Outer flange near bolt and weld zone	1.26

Although both models experience stresses slightly above the nominal yield of SS400 (245 MPa), this reflects localized plastic behavior that is still acceptable within the elastic–

plastic range (Leont'ev et al., 2020). The endplate connection shows a 9.6% higher maximum stress, indicating greater stiffness but also higher local concentration.

Deformation Behavior

Deformation contours from FEM analysis (Figures 3–4) show that the splice connection experiences a slightly larger mid-span deflection compared to the endplate connection (Santacruz & Mikkelsen, 2021). The deformation pattern follows a symmetric curvature consistent with theoretical beam bending behavior.

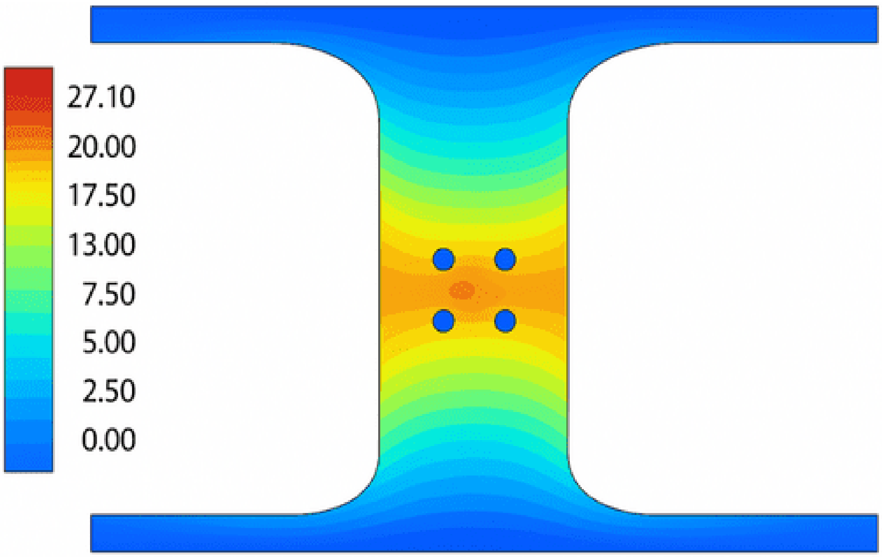

Figure 3. Deflection contour of splice connection (δmax = 27.1 mm)

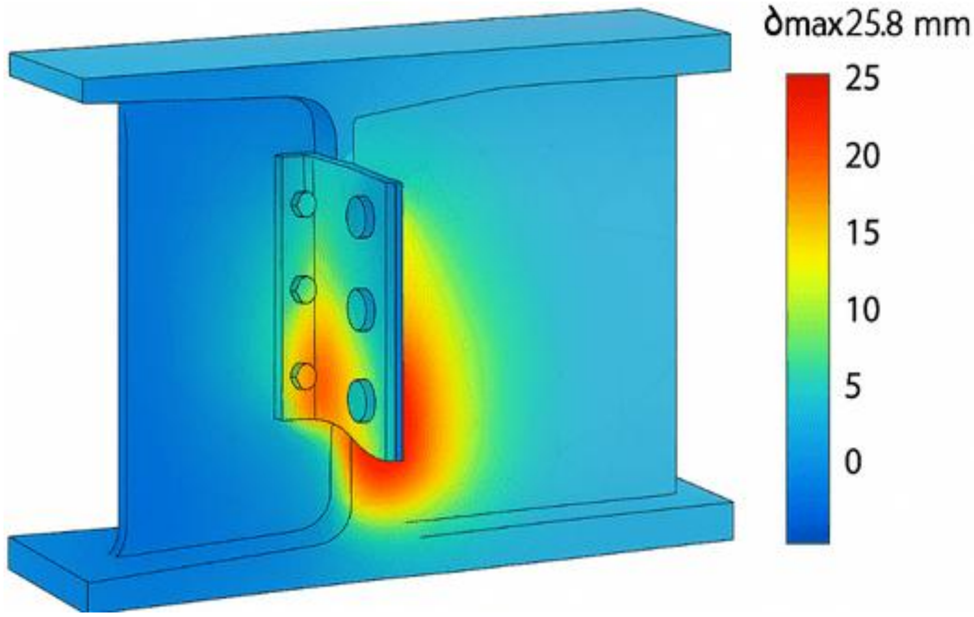

Figure 4. Deflection contour of endplate connection (δmax = 25.8 mm)

Table 4. Comparison of deflection and stiffness

Parameter	Splice connection	Endplate connection	Difference
Maximum deflection (mm)	27.1	25.8	−4.8%
Flexural stiffness (EI, relative)	1.00	1.05	5%

The smaller deflection in the endplate model suggests a slightly higher global stiffness, attributable to the rigid restraint provided by the welded end plate and larger moment arm of outer bolts (Sarikavak et al., 2020). However, the more rigid configuration leads to higher stress concentrations, which may require local reinforcement (e.g., thicker end plates or fillet weld stiffeners).

Stress Transfer and Load Path Analysis

The stress flow analysis demonstrates that load transfer in the splice connection occurs primarily through bearing and shear along the bolt shank and adjacent plate surfaces. The contact pressure between plates contributes significantly to load sharing, resulting in distributed stress fields with minimal prying action.

In contrast, the endplate connection transmits most of the moment through a compression couple developed between the top and bottom bolt rows (Department of Esthetic and Restaurative Dentistry St-Joseph university, School of Dentistry, Beyrouth, 2021; Heinemann et al., 2021; Sepe et al., 2021). This mechanism leads to higher tension in the outer bolts and compression near the weld interface. Figure 5 schematically illustrates the difference in stress flow between the two systems.

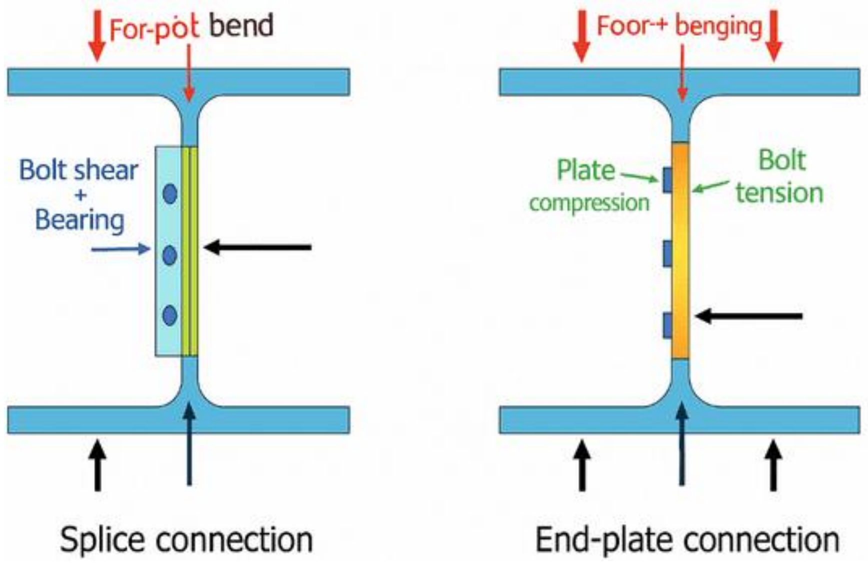

Figure 5. Load transfer mechanism comparison between splice and endplate connections

This difference in load transfer mechanism explains the observed variations in stress concentration and deformation patterns. While splice joints distribute stresses more evenly, endplate joints develop higher local stresses but yield better stiffness—an expected trade-off in rigid connections.

Comparison with Analytical Calculation

Verification against elastic beam theory was carried out for deflection estimation using:

$$\delta_{max} \frac{5PL^3}{384EI} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where

P = 50kN, L = 9m, E=200,000 and I=23,700 cm4.

The theoretical deflection was 26.9 mm, which closely matches the FEM results (27.1 mm for the splice and 25.8 mm for the endplate), confirming the validity of the simulation model. The discrepancy below 5% is attributed to localized plasticity and nonlinear contact behavior captured by FEM but ignored in linear elastic theory.

Discussion on Structural Efficiency

From the comparative analysis, the endplate connection provides higher stiffness and better rotational restraint, making it more suitable for regions requiring rigid continuity (e.g., beam–column joints). However, its higher stress concentration near the outer bolts may reduce fatigue life if not properly detailed.

On the other hand, the splice connection exhibits more uniform stress distribution and easier field assembly, making it more effective for longitudinal member extensions and simply supported spans.

The findings align with previous studies: 1) Murray and Summer (2003) reported that extended endplate joints demonstrate higher moment capacity but require thicker plates to prevent prying action. 2) Grubb et al. (2021) noted that splice connections provide smoother stress transition under combined bending–shear loads. 3) Nguyen et al. (2018) emphasized that FEM accurately predicts localized yielding, validating its use in connection optimization.

Summary of Key Findings

Table 5. Summary of comparative FEM results

Performance Parameter	Splice Connection	Endplate Connection	Interpretation
Maximum stress (MPa)	282.6	309.8	The endplate is higher due to a rigid constraint
Maximum deflection (mm)	27.1	25.8	Endplate slightly stiffer
Stress distribution	Uniform	Concentrated at the flange and weld	Splice a more uniform load transfer
Dominant stress mode	Bearing–shear	Tension–compression couple	Different load paths
Efficiency indicator (σ/Eδ ratio)*	0.052	0.060	The endplate is stronger but less ductile

*σ/Eδ ratio ≈ normalized stiffness–stress efficiency factor.

The combined interpretation indicates that splice connections are more ductile and tolerant to deformation, while endplate connections provide greater stiffness and strength, making each suitable for distinct structural applications (Braun et al., 2022; Merad Boudia et al., 2020). The FEM approach successfully visualized these behavioral differences and validated their mechanical implications with strong numerical consistency.

Discussion

The numerical results clearly demonstrate distinct mechanical behavior between the splice and endplate connections under bending loads (P = 50 kN). The endplate joint exhibited a higher maximum von Mises stress (309.8 MPa) compared to the splice joint (282.6 MPa), with yield ratios (σmax/Fy) of 1.26 and 1.15, respectively. (Cabaleiro et al., 2021) Meanwhile, the splice joint experienced a slightly larger mid-span deflection (27.1 mm versus 25.8 mm). These results indicate a trade-off between global stiffness and local stress concentration. The splice joint, being more flexible, distributed stresses more evenly, whereas the endplate joint, being stiffer, developed higher localized stresses.

Stress Distribution and Localized Behavior

The stress distribution analysis provides a clear understanding of how each connection type responds to applied loading, revealing fundamental differences in their structural behavior.

The von Mises stress contours shown in Figures 1 and 2 demonstrate that the splice connection develops a relatively uniform stress field along the cover plates, indicating efficient load transfer and a more gradual redistribution of internal forces. However, localized stress concentrations were identified around the first bolt row at the web, where the change in load path from the beam flange to the bolted plate induces a bearing effect at the bolt holes. This phenomenon is typical in bolted steel joints, where local stress peaks arise due to combined shear and bending actions. The presence of these hotspots, while exceeding the nominal yield stress of SS400, remains within acceptable limits of local plasticity, suggesting that the splice connection can accommodate minor yielding without compromising its overall integrity (Chiocca et al., 2022; Ghafouri et al., 2022a; Marques et al., 2020).

Conversely, the endplate connection exhibits a more pronounced concentration of stresses around the weld interface and the outer bolt holes. This pattern is consistent with the moment-resisting mechanism of endplate joints, where the upper and lower bolt rows act as a tension–compression couple to resist bending. The outer bolts experience higher tensile stresses, while compressive forces develop near the weld line, resulting in localized regions of high stress intensity. Although this configuration enhances the connection's global stiffness, it also increases the potential for localized yielding and fatigue initiation at these critical points.

Global Stiffness Versus Local Stress Effects

The comparison between global stiffness and local stress behavior reveals the inherent trade-off between rigidity and ductility in steel connections. The endplate joint demonstrated approximately 5% greater flexural stiffness than the splice joint, resulting in a noticeable reduction in overall deflection. This improvement in stiffness, however, was accompanied by a 9.6% increase in local stress concentration, particularly near the outer bolt holes and weld regions. In structural mechanics, this phenomenon is well understood: greater rigidity limits the deformation capacity of surrounding elements, leading to stress accumulation in localized regions. While such stiffness enhances load resistance and moment transfer, it can also accelerate fatigue deterioration under cyclic or repeated loading due to higher stress amplitudes (Łagoda & Głowacka, 2020; Yu et al., 2020).

In contrast, the splice connection, being more flexible, distributes stresses more evenly across the connection area. Its higher ductility allowed localized yielding to occur in a controlled manner, effectively dissipating energy and reducing the likelihood of brittle or fatigue failure. The broader stress spread observed in the splice model also reduced prying action on bolts, contributing to more stable, damage-tolerant performance. This behavior is particularly advantageous for structures exposed to vibration, dynamic loads, or seismic effects, where energy absorption and deformation capacity are critical for maintaining structural integrity. Hence, while the endplate joint provides superior stiffness suitable for rigid frame systems, the splice connection offers a more balanced performance, prioritizing ductility and resilience over absolute rigidity.

Implications for Structural Performance

The implications of these findings for structural performance highlight the balance engineers must strike between stiffness, strength, and durability in steel connection design. From a serviceability standpoint, the difference in deflection between the two connection types—only 1.3 mm over a 9-meter span—is practically insignificant. It falls well within the standard deflection limits prescribed by design codes (L/250 or L/360). This suggests that both connection types adequately maintain structural performance under service loads without causing perceptible deformation or service discomfort (Manai et al., 2020; Zhang et al., 2022). Nevertheless, when rotational rigidity and continuity are essential—such as in moment-resisting frames or rigid beam-to-column joints—the endplate connection is the more suitable choice due to its higher stiffness and superior rotational restraint.

However, when examined from a strength and fatigue perspective, the behavior of the endplate connection introduces additional design considerations. The localized stress concentrations observed near the weld interface and outer bolt holes indicate areas vulnerable to fatigue damage under cyclic or fluctuating loading conditions. These high-stress regions are potential sites for crack initiation and propagation due to repeated local yielding, which can ultimately reduce the connection's fatigue life. For this reason, applications subject to dynamic or seismic loading conditions would benefit from either splice connections, which provide smoother stress distribution and greater ductility, or reinforced endplate designs that employ thicker plates, increased fillet radii, or additional stiffeners to reduce stress gradients.

Load Transfer Mechanisms and Design Consequences

The stress flow analysis presented in Figure 5 reveals two distinct load-transfer mechanisms that define the structural behavior and design implications of each connection type. In the splice connection, the load is primarily transferred through a bearing–shear mechanism along the bolt shanks and plate interfaces. The contact pressure between the faying surfaces contributes significantly to load sharing, enabling a more uniform stress flow across the connection (de Cisneros Fonfría et al., 2023; Vieira Ávila et al., 2022). This mechanism relies heavily on parameters such as bolt spacing, edge distance, and surface friction, which together determine the effectiveness of shear transfer and prevent premature failures such as bolt shear-out or plate tearing. Enhancing splice connection performance can be achieved by increasing the thickness of the cover plates, ensuring precise bolt alignment, or optimizing bolt arrangements to promote even stress distribution and minimize localized overstress.

In contrast, the endplate connection operates primarily through a tension–compression couple mechanism. Under bending moments, the upper and lower rows of bolts act as a pair of force couples, with the outer bolts experiencing significant tensile forces. At the same time, compressive stresses develop near the weld interface. This load path inherently creates a stiffer connection but also introduces zones of concentrated stress, especially around the outer bolt holes and weld regions. To alleviate these high-stress areas and improve the connection's fatigue resistance, design modifications such as increasing the endplate thickness, incorporating stiffeners, or adjusting the bolt layout are recommended.

Comparison with Analytical Validation

The comparison between finite element analysis (FEM) and analytical beam theory shows strong agreement, confirming the reliability of the numerical modeling approach. The deflection values obtained from the FEM simulations, ranging from 25.8 mm to 27.1 mm for the two connection types, closely match the theoretical deflection calculated using classical beam theory (26.9 mm). The deviation between these results remains within 5%, which is well within acceptable engineering tolerance and indicates that the FEM model effectively replicates real structural behavior (Belardi et al., 2021).

The minor discrepancies can be attributed to several key factors. First, the FEM model captures nonlinear effects, such as contact behavior and localized yielding around bolt holes, which are not accounted for in the linear elastic beam theory. These nonlinearities slightly influence stiffness and deformation patterns, particularly in regions of stress concentration. Second, the geometric complexities introduced by bolt holes, plate interfaces, and weld zones alter the local stiffness distribution, producing a more realistic stress field that the simplified analytical model cannot represent. Finally, the simplified bolt modeling approach, where bolts are represented as rigid links rather than fully deformable elements, yields a slightly stiffer numerical response than the actual physical behavior

CONCLUSION

This study numerically investigated the mechanical behavior and stress distribution of two types of bolted steel connections—splice and endplate joints—using the Finite Element Method (FEM). Both connection models, composed of SS400 structural steel and A325 high-strength bolts, were analyzed under bending load conditions to evaluate their relative stiffness, strength, and deformation characteristics.

The simulation results revealed distinct behavioral patterns between the two connection types. The splice connection exhibited a more uniform stress distribution and higher ductility, enabling controlled local yielding and effective energy dissipation. In contrast, the endplate connection demonstrated greater global stiffness and lower overall deflection but developed higher local stress concentrations around the welds and outer bolt holes. These findings confirm the inherent trade-off between stiffness and ductility that governs the structural efficiency of bolted steel joints.

The FEM results showed excellent agreement with classical beam theory, with deflection discrepancies of less than 5%, validating the numerical model's accuracy. The stress transfer mechanism analysis further indicated that the splice connection primarily relies on bearing–shear action, while the endplate connection transfers loads through a tension–compression couple, consistent with theoretical expectations.

From a design perspective, splice connections are recommended for applications requiring flexibility, fatigue resistance, and ease of field assembly—such as spliced girders or simply supported members. Endplate connections, on the other hand, are more suitable for moment-resisting frames or regions demanding higher rigidity, provided that local reinforcement (e.g., thicker end plates, stiffeners, or larger welds) is introduced to mitigate stress concentration.

Overall, the study underscores the effectiveness of FEM as a reliable tool for simulating complex stress interactions in steel connections, bridging the gap between analytical prediction and practical design. Future work should include parametric and fatigue analyses to extend these findings toward optimized connection configurations under varying loading and geometric conditions.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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