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Review

Behavior, Analysis, and Design of Semi-Rigid Extended End-Plate Connections in Steel Frames: A Comprehensive Review

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Abstract

This review synthesizes findings from more than 100 journal articles, reports, and design standards on the design, simulation, and testing of steel beam-to-column connections, with emphasis on semi-rigid bolted extended end-plate (EEP) joints. The core objective of this study is to highlight the critical importance of accurately capturing this semi-rigid behavior, given the significant implications of improper modeling for the global response, safety, and design reliability of steel frames. While connections are often idealized as fully rigid or pinned, EEP connections typically exhibit a semi-rigid response governed by nonlinear moment–rotation (M–θ) behavior. The reviewed literature is organized around: (i) mechanical response and key failure mechanisms (end-plate yielding, bolt fracture, and prying action); (ii) analytical and numerical prediction methods, including component-based models and finite-element approaches capable of representing contact, bolt pretension, and cyclic degradation; and (iii) system-level implications for steel frames. Approaches used in major standards (AISC and Eurocode 3) for classifying connection stiffness and strength are compared, and experimental programs are summarized to identify the dominant parameters controlling resistance, ductility, and failure mode. Translating these component-level findings to the structural-system level, the review highlights how appropriately detailed semi-rigid EEP connections can enable moment redistribution, reduce member demands, and support stable inelastic deformation under seismic actions. Key research gaps include three-dimensional and multiaxial loading, impact and other high-rate actions, and the performance of alternative materials such as stainless steel.

Keywords: semi-rigid joints; steel frames; moment–rotation behavior; extended end-plate connections; seismic energy dissipation; simulation

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1. Introduction

Beam-to-column connections are critical components of steel frames. They transfer axial forces and bending moments and strongly influence global stability and structural performance [1,2]. Conventional analysis idealizes these joints as either fully rigid (no relative rotation) or pinned (no moment transfer) [3,4]. Experimental evidence shows that real behavior, particularly for bolted joints, typically falls between these extremes, exhibiting a nonlinear moment–rotation response characteristic of semi-rigid connections [2,5]. Ignoring semi-rigid behavior can lead to inaccurate predictions, including underestimated lateral displacements and misallocated internal force demands [1,6]. Figure 1 presents a schematic

representation of the continuous moment–rotation (M-θ) behavioral response of beam-to-column connections. The curves illustrate how connection behavior is conceptually classified into three regions based on stiffness and strength boundaries: the light blue-shaded region denotes a fully restrained (rigid) connection, the light green-shaded region denotes a simple (pinned) connection, and the intermediate tan-shaded region represents a semi-rigid connection. In this schematic, $S_{j,ini}$ represents the initial rotational stiffness, while M_u and θ_u denote the ultimate moment capacity and corresponding rotation, respectively.

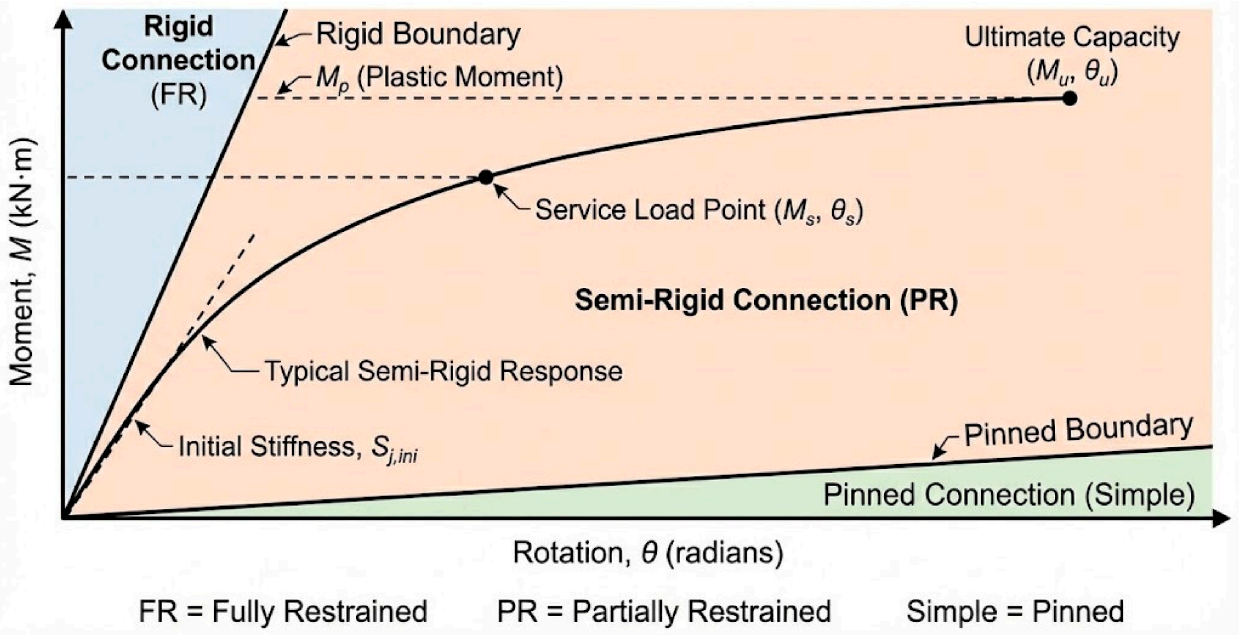


Figure 1. Schematic representation of beam-to-column moment–rotation (M-θ) behavioral response and conceptual boundaries for connection classification.

Among semi-rigid connections, the extended end-plate (EEP) connection is widely used in steel construction. It transfers significant moments and offers good constructability, and it typically exhibits higher stiffness than other bolted connections [7,8]. In an EEP joint, a thick steel end plate is welded to the beam end and bolted to the column flange. The plate extends beyond the top and bottom beam flanges, allowing additional bolt rows and increasing the joint's tension capacity [8–10]. Figure 2 shows the schematic illustration of the EEP connection. Although EEP connections are often designed as fully rigid, experiments show that they exhibit semi-rigid behavior governed by end-plate bending, bolt elongation, and prying action (forces generated when the plate lifts around the bolt head or nut) [9,11]. Stiffeners (ribs) are flat steel strips that can improve this behavior by increasing flexural strength, yield rotation, and energy dissipation capacity [11–13].

Recognizing and modeling semi-rigid behavior offers both structural and economic advantages. Here, a semi-rigid connection is defined as a beam-to-column joint that is neither perfectly pinned nor fully rigid; it provides partial rotational restraint under load. From an economic standpoint, semi-rigid connections facilitate the redistribution of internal bending moments within the frame. This structural redistribution, in turn, permits the use of lighter beams than those required in simple frames and lighter columns than those required in rigid frames [2,14–16]. Consequently, the primary economic benefit derives from these material savings, with reported studies indicating that such connections can significantly reduce total steel weight while maintaining required safety and performance [17,18].

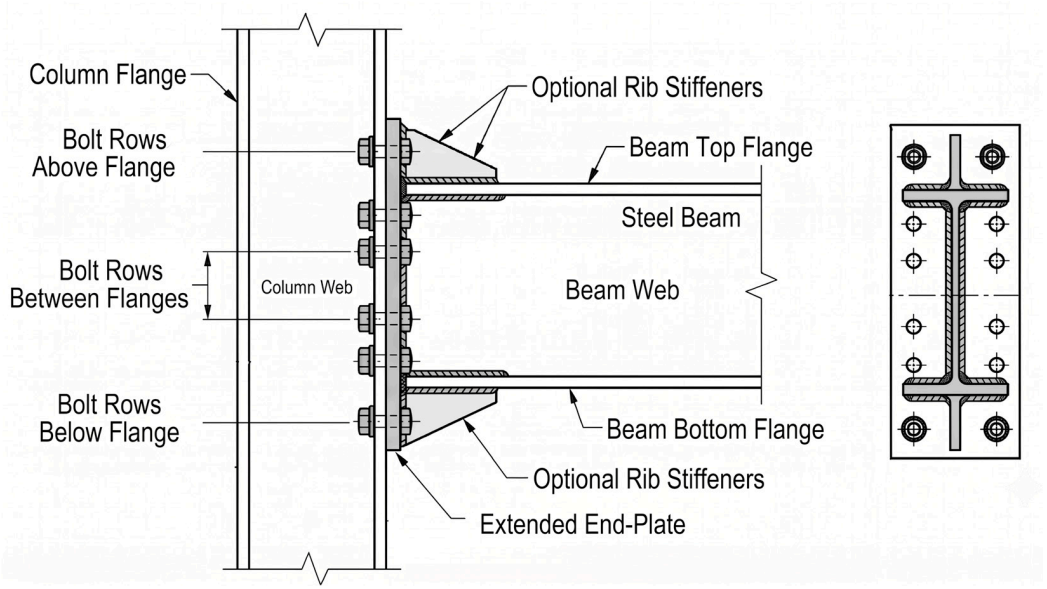


Figure 2. Schematic illustration of EEP connection.

Structurally, semi-rigid connections allow limited relative rotation between components, increasing ductility and energy absorption, which is beneficial in seismic regions [19,20]. Following the failures of welded connections during the 1994 Northridge and 1995 Kobe earthquakes, bolted semi-rigid connections were promoted as more reliable alternatives; these joints can exhibit stable hysteretic behavior under cyclic loading [14,21]. Increased joint flexibility lengthens the natural period and can reduce seismic base forces, but it may also increase interstory drift, which must be controlled [14,19,22]. Properly designed semi-rigid frames more readily satisfy the strong-column weak-beam philosophy, reducing the risk of soft-story mechanisms [14,23]. The mechanical behavior and failure modes reported in previous studies are summarized in Figure 3, which also highlights common design approaches such as the component method. These failure modes are discussed in the following sections.

Recent advances in structural engineering have led to studies of steel and composite beam–column end-plate connections under varied loading conditions. For example, Wang et al. examined bolted end-plate connections and showed that column web thickness controls the joint failure mode—panel-zone shear or beam plastic hinging [24]. For composite systems, Boukhalkhal et al. found that concrete infill in square hollow-section columns improves rigidity, strength, and energy dissipation [25]. Nie et al. introduced an outer diaphragm to connect steel beams to circular columns, preventing stress concentration and ensuring ductility [26]. Guo et al. showed that weak-axis end-plate joints with cross-shaped stiffeners increase bearing capacity and stiffness [27]. For sustainable construction, Abdulkarim et al. studied deconstructable external composite joints using precast geopolymer slabs and bolted connectors, achieving stable energy dissipation and strong semi-rigidity [28]. Wang et al. explored retrofitting with prefabricated cover plates under preload, boosting load-bearing and reducing end-plate separation [29]. Li et al. analyzed progressive collapse of steel substructures under fire and column loss, revealing that load resistance shifts from bending to catenary action at high temperatures [30].

Despite these advantages mentioned above, semi-rigid frames are not widely adopted in practice, in part because predicting the rotational stiffness of beam-to-column joints remains challenging, and unified design tools are still lacking in most structural software packages [2,31]. The performance of EEP connections depends on factors such as end-plate thickness, bolt diameter, and the presence of stiffeners. Their behavior can be evaluated using advanced analytical approaches, including the component method and finite element

modeling [7,32]. This review synthesizes research on the behavior, analysis, and design of EEP connections in steel frames, covering mechanical properties, performance under static and seismic loading, and modeling strategies for partial joint flexibility. The goal is to bridge findings at the connection level with the design of complete steel frame systems. Table A1 summarizes key studies and their main findings.

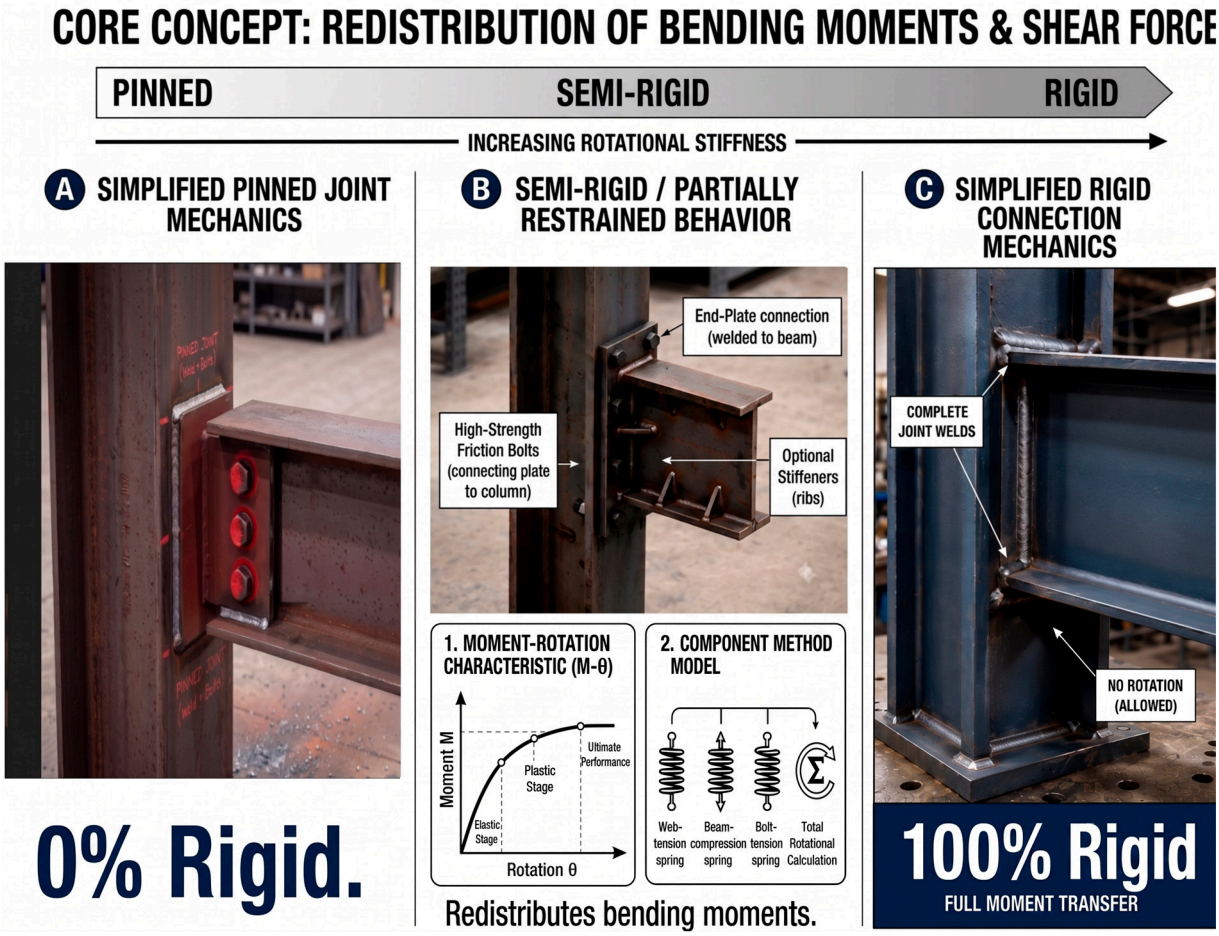


Figure 3. Schematic diagram illustrating pinned, semi-rigid, and rigid beam-to-column connections and their corresponding mechanical behavior.

The remaining contents are structured as follows. Section 2 briefly introduces the classification and design standards, followed by Section 3 on the experimental research and Section 4 on the numerical and analytical modeling methods. Section 5 primarily focuses on applications of extended end-plate connections in structural systems, while Section 6 emphasizes the seismic behavior and cyclic loading response of EEP connections. Section 7 synthesizes existing research findings and identifies research gaps. Finally, conclusions and recommendations are presented in Section 8.

2. Classification and Design Standards

Accurate modeling of steel frames depends on how beam-to-column connections are classified. Traditionally, connections were idealized as either fully rigid (no rotation) or perfectly pinned (free rotation). In practice, most connections exhibit nonlinear moment–rotation behavior and develop permanent deformations; hence, semi-rigid connections lie between these extremes [2]. Modern design codes classify connection behavior by stiffness (resistance to deformation), strength (moment capacity), and ductility (ability to deform

without loss of integrity). These parameters define connection response and are particularly important for extended end-plate connections.

2.1. Technical Boundaries of Connection Rigidity

Connections are commonly characterized by moment–rotation (M-θ) curves, which relate bending moment to joint rotation.

- Rigid (fully restrained) connections provide high rotational stiffness, maintaining the beam–column angle nearly constant under load. They transfer significant moments and are essential to frame action stability in unbraced frames.
- Pinned (simple) connections transmit shear and axial forces but little or no moment. They allow free rotation, have low stiffness, and are typical in braced frames.
- Semi-rigid (partially restrained) connections have intermediate stiffness, carry a portion of the bending moment, and permit noticeable rotation. This partial restraint affects moment distribution and lateral displacements throughout the frame.

2.2. AISC Classification Methodology

The American Institute of Steel Construction (AISC) specifications, specifically ANSI/AISC 360, classify connections into three categories: Fully Restrained (FR), Partially Restrained (PR), and Simple [33,34].

AISC uses a classification index based on secant stiffness (K_s), defined as the ratio of moment (M_s) to rotation angle (θ_s) under normal service loads. These boundaries are normalized against the flexural stiffness of the connected beam (EI/L, where E is Young's modulus, I is the moment of inertia, and L is the beam length):

- FR (rigid): $K_sL/EI \geq 20$.
- Simple (pinned): $K_sL/EI \leq 2$.
- PR (semi-rigid): $2 < K_sL/EI < 20$ [33].

Regarding strength, AISC specifies that a connection is considered simple if it transmits less than 20% of the beam's plastic moment (M_p) at a rotation of 0.02 radians [33]. For end-plate connections specifically, AISC Design Guide 16 and AISC 358 use yield-line theory to predict the strength of the end-plate and column flange, often intended to design these as FR connections for seismic applications [35,36]. However, experimental studies show that many connections detailed as FR actually fall into the PR category when assessed against the stiffness boundaries, particularly when column flanges are unstiffened [33].

2.3. Eurocode 3 Classification Methodology

Eurocode 3 (EN 1993-1-8) adopts a more granular approach known as the "Component Method" to classify joints by both stiffness and strength. This method disassembles the joint into basic components (e.g., column web in compression, column flange in bending, bolts in tension), assigns a stiffness coefficient (k_i) to each, and uses them to calculate the initial rotational stiffness, $S_{j,ini}$ [11,33].

The stiffness boundaries in Eurocode 3 depend on whether the frame is braced or unbraced:

- Rigid: $S_{j,ini} \geq k_bEI_b/L_b$, where $k_b = 8$ for braced frames and $k_b = 25$ for unbraced frames.
- Nominally pinned: $S_{j,ini} \leq 0.5\, EI_b/L_b$.
- Semi-rigid: Connections falling between these limits [33,37].

For extended end-plate connections, Eurocode 3 utilizes the "equivalent T-stub" method to model the tension zone. This approach calculates the effective length of the T-stub to predict failure modes, including complete flange yielding (Mode 1), bolt failure

with flange yielding (Mode 2), and bolt failure only (Mode 3) [9,11]. Research indicates that Eurocode 3 often yields a more reliable classification index for end-plate connections than simplified bilinear models. To approximate the highly nonlinear moment–rotation characteristics of joints, several representative simplified bilinear models are commonly reported in the literature:

The Standard Bilinear Model: This model uses three main parameters to represent behavior: the initial rotational stiffness, the plastic moment, and the plastic rotational stiffness [38]. Its main feature is a sharp change in rigidity at the transition moment (the intersection of the two curves), followed by a relatively shallow second slope. In some applications, this is adapted into a symmetric bilinear elasto-plastic model with kinematic hardening to account for cyclic loading behavior [14].

The Half-Initial Secant Stiffness Method: This simplified bilinear model is widely adopted for its appropriate balance between computational rigor and ease of implementation. A key feature of this method is the use of a reduction factor (η) applied to the initial rotational stiffness. Typically, the initial stiffness is halved (or reduced by a factor of 2.0) when the required bending moment exceeds 2/3 of the joint's moment resistance [17,31].

Eurocode 3 Simplified Bilinear Approach: For elastic-plastic analysis, Eurocode 3 provides a simplified bilinear moment–rotation curve. The initial rotational stiffness ($S_{j,ini}$) is maintained up to 2/3 of the joint's design moment resistance ($M_{j,Rd}$). The stiffness is subsequently modified by a reduction coefficient (μ) for applied design bending moments ($M_{j,Ed}$) between $2/3M_{j,Rd}$ and $M_{j,Rd}$ [11,38].

Although Eurocode 3's comprehensive component method is generally more reliable than these simplified approaches, research shows it may overestimate the initial stiffness in stiffened configurations [11,33].

3. Experimental Research on Extended End-Plate Connections

The experimental research landscape for semi-rigid connections encompasses a broad range of static and cyclic testing campaigns to characterize moment–rotation (M-θ) behavior, validate failure mechanisms, and establish classification indices. Researchers have extensively used full-scale testing of beam-to-column sub-assemblages and frames to determine the effects of geometric variables, such as end-plate thickness, bolt configuration, and stiffener arrangements.

3.1. Static Loading Campaigns

Static experimental programs have been fundamental in defining the initial stiffness and ultimate capacity of semi-rigid connections. Maali [39] conducted tests on six full-scale beam-to-column connections to examine the influence of vertical and horizontal stiffeners on IPE profile end-plate connections. The study observed that while both stiffener types improved resistance, the failure mode consistently manifested as Mode 2 (end-plate yielding followed by bolt fracture), with vertically stiffened models exhibiting a deeper V-shaped deformation at failure. Similarly, Abidelah et al. tested eight specimens to evaluate the impact of stiffeners on flush and extended end-plates. Their results indicated that stiffeners significantly reduced plate deformation in the extended zone, altering the internal force distribution. Failure in beam-to-column specimens typically initiated with column flange yielding in the tension zone, followed by column web buckling in the compression zone [11].

Investigating the specific influence of bolt spacing and plate thickness, Arul et al. tested eight extended end-plate specimens. They found that increasing end-plate thickness shifted the failure mode from end-plate tearing to tension-bolt fracture due to reduced prying action and increased stiffness. Conversely, wider bolt spacing reduced initial stiffness

and load-carrying capacity by increasing the prying lever arm [40]. Maggi et al. further supported these conclusions using parametric analyses calibrated versus experimental data, noting that thinner plates showed significant double-curvature deformation and prying action. In contrast, thicker plates behaved more rigidly with reduced plastic influence from the plate itself [9].

3.2. Cyclic Loading and Seismic Performance

Cyclic testing has been essential in assessing the energy transformation and ductility of semi-rigid connections. Faridmehr et al. subjected eight full-scale unstiffened EEP connections to AISC seismic loading procedures. The results showed that unstiffened EEP connections failed to develop the full inelastic capacity of the connected beams, with plastic hinges forming primarily within the connection components (end plates and bolts) rather than in the beam section. This contrasted with SidePlate connections, which exhibited full hysteretic loops and rigid behavior [33].

In a comprehensive study of failure modes at different performance stages, Lu et al. tested a 1/2-scale semi-rigid steel frame. They identified a distinct failure sequence: end-plate yielding, followed by beam-end yielding, and finally column-base buckling. This study demonstrated the key role of the end-plate-to-column flange thickness ratio ($\delta = t_e/t_{fc}$); increasing this ratio significantly improved lateral stiffness and bearing capacity but gradually reduced ductility [41]. Further research by Lu et al. on 3D frames confirmed that, under strong-axis cyclic loading, failure was controlled by weld fractures at the column base after significant beam-end buckling [21].

Yılmaz et al. provided a comparative study of bolted stiffened end-plate (BSEP) and bolted flange-plate (BFP) connections using European profiles. The BSEP connections failed due to the fracture of the beam top flange and web following local buckling. In contrast, the BFP connections exhibited self-untightening of the nuts and slip between the flange plate and beam flange, indicating different energy-absorption mechanisms [42]. Expanding to multi-axial behavior, Shi et al. tested spatial joints with major-axis T-stubs and minor-axis end-plate connections. They observed that the major-axis connections failed via T-stub fracture, while the minor-axis connections failed through substantial end-plate bending. The study found that increasing the end-plate thickness reduced the ductility of the minor-axis connection [43].

3.3. Primary Variables and Failure Modes

The experimental bodies of work collectively identify several primary variables governing connection behavior:

- **End-plate thickness:** Thinner plates generally lead to ductile failure modes characterized by extensive plate yielding (Mode 1) and prying action, whereas thicker plates transfer failure to the bolts (Mode 3) or to the welds [9,40].
- **Stiffeners:** The presence of rib stiffeners generally increases moment capacity and reduces plate deformation, but can reduce overall ductility by concentrating stresses, leading to bolt or weld fractures [11,39].
- **Bolt configuration:** Larger bolt diameters and optimized spacing enhance ultimate capacity. Kukla et al. noted that under impact loading, bolted joints exhibited high structural ductility, with significant deformations in the bolt connectors and unstiffened column webs [44].

The interplay of these geometric and mechanical variables strictly dictates the distribution of forces, the degree of prying action, and the yielding sequence within the joint, thereby determining its ultimate collapse mechanism [8,9]. Depending on how these spe-

cific parameters are configured, the most frequently observed physical failure modes across the reviewed studies include:

- **End-plate yielding:** Characterized by excessive bending and formation of yield lines, commonly occurring in connections with thin plates [41,43].
- **Bolt fracture:** Often occurring in stiffened or thick-plate connections in which prying forces are minimized, or as a secondary failure following plate yielding (Mode 2) [39,40].
- **Column flange yielding:** Observed in tension zones, particularly when column flanges are relatively thin compared to the connection components [11].
- **Local buckling:** Occurring in beam flanges or column webs during the ultimate stages of loading, frequently serving as the final failure mechanism in semi-rigid frames [41,42].

We summarize Section 3.3, which examines the relationship between the primary variables and the failure modes, as shown in Figure 4.

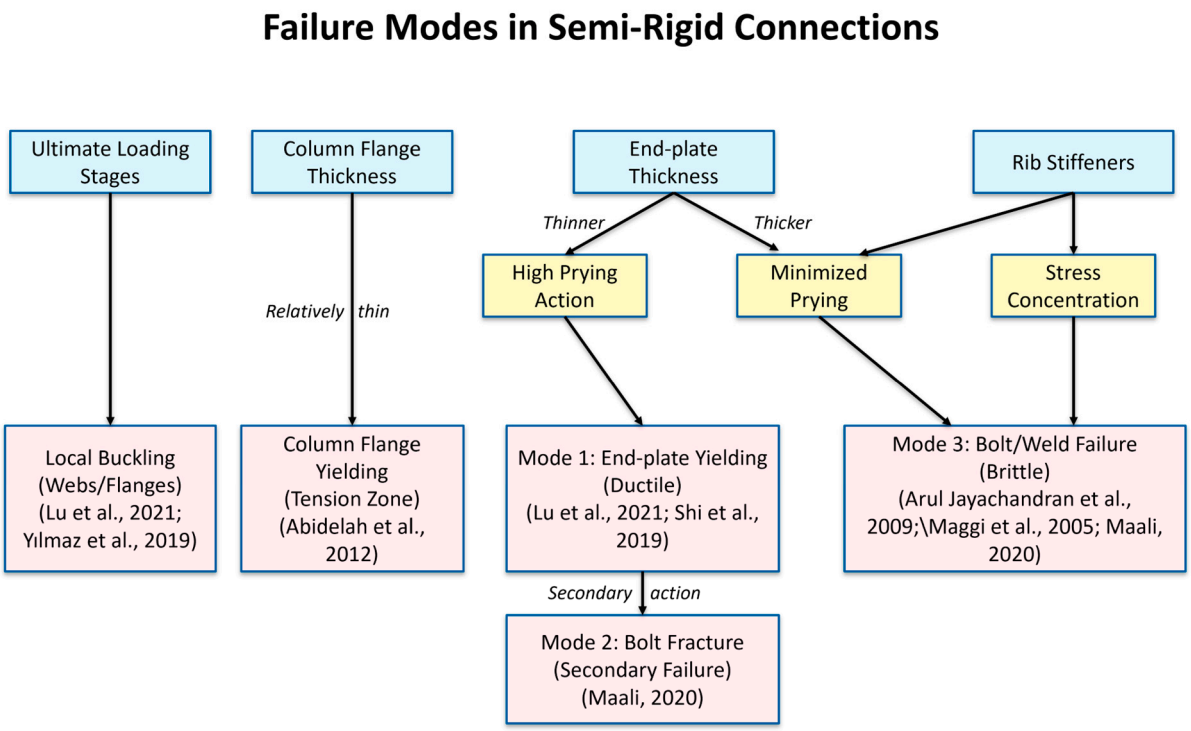


Figure 4. Relationship between the primary variables and failure modes (The mentioned references are Lu et al., 2021 [41], Yılmaz et al., 2019 [42], Abidelah et al., 2012 [11], Shi et al., 2019 [43], Maali et al., 2020 [39], Arul Jayachandran et al., 2009 [40], and Maggi et al., 2005 [9]).

3.4. Influence of Bolt Pretension on Connection Behavior

Bolt pretension is crucial for the mechanical behavior of extended end-plate connections and T-stubs, strongly affecting stiffness, strength, slip resistance, and cyclic performance.

- **Slip Resistance and Mechanism:** When pretension is applied, the bolt and the surrounding plate act as an integral unit to jointly bear the external load, whereas bolts without pretension act as independent units [45]. This preloading prevents the early sliding of connected parts. Under codes such as EN 1993-1-8, pretensioned high-strength bolts are explicitly required for Category B (slip-resistant at serviceability) and Category C (slip-resistant at ultimate) connections to prevent slip under various loading conditions [46].
- **Stiffness and Ultimate Strength:** The application of bolt pretension substantially increases both the initial rotational stiffness and the moment capacity of the con-

nection [23,45]. Analytical and finite element studies demonstrate that higher bolt pretension forces lead to a more pronounced improvement in initial rotational stiffness than in moment resistance. For instance, joints with snug-tightened bolts can exhibit approximately 15% lower initial rotational stiffness and 5% lower moment resistance than those with benchmark pretension ratios [47]. Furthermore, varying bolt pretension can alter the ultimate moment–rotation behavior by up to 25% [48], and studies on T-stubs have shown that using bolts with a 70% preload can yield an ultimate load up to 30% higher than with 0% preloaded bolts [49].

- **Cyclic Performance and Energy Dissipation:** Pre-tensioning the bolts is extremely important to fully utilize the connection's ductility and energy dissipation capabilities under cyclic loading. The preload level, along with parameters such as flange thickness, directly influences the joint's failure modes. For example, the combination of highly prestressed bolts and large flange thicknesses can shift the connection's failure mode toward Mode 3 (bolt fracture), leading to greater bolt plastic deformation and altering the joint's energy dissipation characteristics [49,50].

3.5. T-Stub Analogy and Failure Mechanisms

The T-stub model is a widely used simplified approach for representing extended end-plate connections, as shown in Figure 5. In this model, the column flange or end-plate is like the flange of a T-stub, the beam or column web is like the web of a T-stub, and the bolts connect the two flanges in tension [51,52]. This approach forms the basis of the component method in Eurocode 3.

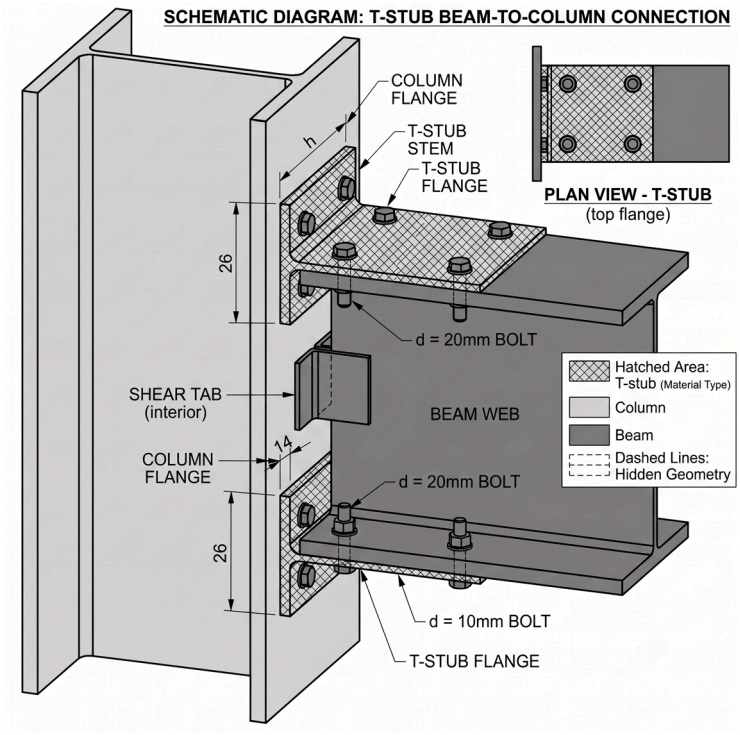


Figure 5. Schematic illustration of the T-stub connection.

Three primary failure modes are recognized in the T-stub model: (1) Mode 1 (Complete flange yielding)—the T-stub flange undergoes full plastic yielding before bolt failure, characterized by plastic hinges at the flange-to-web junction and bolt line, resulting in a ductile mechanism [49]; (2) Mode 2 (Bolt failure with flange yielding)—a mixed mode where the flange yields while bolts reach tensile capacity simultaneously [11,49]; (3) Mode 3 (Bolt fracture)—bolts reach ultimate tensile capacity before significant flange yielding,

a brittle mode typically avoided in design. The T-stub effective length, governed by bolt layout and plate geometry, determines which failure mode governs. Eurocode 3 provides standardized effective length equations based on yield-line patterns [9,51].

To sustain catenary action under such extreme deformations, it is imperative that the connection avoid premature failure and exhibit high ductility. One of the major drawbacks of extended end-plate connections under high rotational demands is the formation of plastic hinges in the end plate, which induces additional tensile demands on the bolts due to prying action. If these prying forces are not strictly managed, they can lead to premature brittle fracture of the bolts before the required large rotations and catenary capacities are achieved [23].

To prioritize ductile yielding over brittle bolt fracture, engineers must carefully balance the connection's geometric parameters. Specifically, it is necessary to limit the end-plate thickness relative to the bolt diameter to ensure that the connection yields in bending (Mode 1 failure) rather than fracturing the bolts abruptly (Mode 3 failure) [8,51]. While thicker end-plates resist bending and prying better, they transfer tension directly to the bolts, leading to a sudden loss of rotation capacity. Alternatively, the application of end-plate stiffeners is a highly effective strategy to curtail the detrimental effects of prying forces. By ensuring the continuity of the beam web, stiffeners distribute the flange forces much more evenly across the bolt group, significantly reducing local prying action and stress concentrations, thereby protecting the bolts from early fracture while enhancing overall energy dissipation and yield rotation of the connection [11,53].

4. Numerical and Analytical Modeling Methods

Numerical modeling, particularly the Finite Element Method (FEM), has become indispensable for analyzing semi-rigid connections, providing a cost-effective alternative to expensive, time-consuming, full-scale experimental testing [54,55]. These models allow for extensive parametric studies to predict nonlinear behavior, failure modes, and stress distributions that are difficult to measure physically [8,23].

4.1. Finite Element Modeling Techniques

Researchers extensively utilize general-purpose software packages such as ABAQUS 2018 and ANSYS 10.0 to develop three-dimensional solid models of connections [55,56]. To faithfully capture the complex behavior of semi-rigid joints, these models must account for both geometrical and material nonlinearities [8,9].

4.1.1. Material and Geometric Nonlinearity

Material nonlinear behavior is typically handled using constitutive laws based on the von Mises yield criterion, with isotropic or kinematic hardening rules [32,54]. For steel components, researchers regularly employ trilinear or bilinear stress–strain curves defined by yield strength (f_y), ultimate strength (f_u), and elastic modulus (E) [54,57]. Some studies utilize true stress–strain relationships derived from coupon tests to improve accuracy, particularly in the post-yield range [47]. Geometric nonlinearity is incorporated to simulate large-displacement effects and membrane actions in thin connecting elements, such as end plates, during ultimate loading stages [9,58].

4.1.2. Bolt Pretension Modeling

Correctly simulating bolt pretension is vital for representing the initial stiffness and slip resistance of connections [48]. Techniques for applying pretension include:

- **Bolt load feature:** Applying specific software commands (e.g., "BOLT LOAD" in ABAQUS) to apply a clamping force to the bolt shank [8,47].

- **Thermal analogy:** Applying heat gradients to the bolts to induce thermal contraction, thereby generating the required tensile stress [9,48].
- **Initial strain:** Assigning initial stress or strain values to link elements representing the bolts [59].

Bolts are frequently modeled as solid cylinders comprising a head, shank, and nut, with mesh densification in these regions to capture stress concentrations [47,55].

4.1.3. Contact and Friction

The interaction among connection components (e.g., end-plate-to-column flange, bolt head-to-plate) is complex and demands strong contact algorithms. Researchers predominantly use "surface-to-surface" contact definitions [57,60]. The normal behavior is typically implemented using "hard contact" to prevent penetration between surfaces, frequently employing Augmented Lagrangian formulations [40,57]. Tangential behavior is simulated using penalty functions using Coulomb friction models [47,61]. Friction coefficients (m_u) generally range from 0.2 to 0.45, depending on the surface treatment, with m_u = 0.3 being a common value for steel-to-steel interfaces [40,55,57].

4.2. Component-Based Modeling

Analytical methods frequently rely on the Component Method (CM), the framework adopted by Eurocode 3 Part 1–8 [8,56]. This method breaks down the joint into basic mechanical components (e.g., a column web in compression, an end-plate in bending, and bolts in tension), each modeled as a translational spring with specific stiffness and strength characteristics [21,58]. These components are assembled to calculate the global moment–rotation (M-θ) response [56].

The frequent use of the CM in practical engineering stems from its distinct advantages over alternative evaluation methods. While experimental testing provides the most reliable data on joint behavior, it is generally too expensive and time-consuming for everyday design practice [62]. Similarly, although refined FEA can accurately capture complex material and geometric nonlinearities, it remains computationally expensive, requires specialized expertise, and is often considered impractical or inconvenient for routine structural design. In contrast, the CM offers a much simpler and highly effective approach for designers [52]. By isolating individual sources of strength and displacement, the CM allows for a more detailed understanding of the connection's behavior [9]. Furthermore, investigating each component separately facilitates the easy control of failure modes through the implementation of local capacity design rules [63].

Recent improvements have led to the Component-Based Finite Element Method (CBFEM), which combines the analytical component method with finite element analysis. This approach, implemented in software such as IDEA StatiCa, enables the analysis of complex joint geometries employing meshing components with shell elements whilst preserving the efficiency of the component method for bolts and welds [56,62].

4.3. Comparison Versus Experimental Data

Numerical models are carefully validated by comparing their outputs against experimental data, with particular focus on moment–rotation (M-θ) curves and physical failure modes [8,55]. Validated models generally show good agreement in the elastic range and ultimate capacity, even though discrepancies in initial stiffness are sometimes observed. As highlighted in the literature, these differences in initial stiffness can be explicitly traced back to two distinct categories: modeling assumptions and experimental uncertainties [55].

Modeling assumptions generally lead to an overprediction of the initial stiffness in finite element models. These numerical idealizations include applying simplified boundary

conditions (e.g., ignoring the column's connection to the strong floor), assuming perfect contact between components without slippage, and simplifying the complex stress–strain behavior of the materials [9,64]. Furthermore, models often omit the initial geometric imperfections and residual stresses that are naturally present in the actual steel members [7].

Conversely, experimental uncertainties encompass the physical realities and imperfections inherent in laboratory testing, which typically reduce the measured stiffness relative to theoretical predictions. These include minor geometric imperfections and manufacturing tolerances, unavoidable slips in the loading frame and its connection to the actuator, and imperfections originating from the assembly of the test models [7,9,65]. A critical experimental uncertainty is the unexpected loss of bolt pretension during the assemblage sequence, leading to the full pretension load simulated in the FE models not being achieved in physical tests.

Despite these discrepancies in the initial elastic stage, FEM has been shown to accurately predict specific failure mechanisms such as end-plate yielding, bolt fracture, and local buckling observed in laboratory settings [54,61]. Once calibrated, these numerical models serve as reliable tools for conducting parametric studies of variables such as plate thickness, stiffener configuration, and bolt diameter [8,9].

5. Application in Structural Systems

The incorporation of semi-rigid connections into structural analysis significantly alters the large-scale behavior of steel frames, impacting global stability, deformation characteristics, and the distribution of internal forces. By closing the gap between idealized, fully rigid, and nominally pinned models, semi-rigid connections offer a more realistic representation of frame performance, which is key for improving material use and assessing safety against collapse mechanisms [2].

5.1. Lateral Frame Drift and P-Delta Effects

The flexibility of beam-to-column connections is a primary determinant of a frame's lateral stiffness. Research regularly indicates that reducing connection stiffness from rigid to semi-rigid conditions increases lateral drift under static loading [1,4]. For instance, numerical investigations have shown that changing connections from rigid to semi-rigid with low rotational stiffness (e.g., $10EI/L$) can increase maximum horizontal displacement by approximately 12% [1]. Furthermore, the interaction between connection flexibility and second-order effects is significant; the P-Delta effect amplifies inter-story drifts, particularly when the percentage of rigid connections in a frame drops below 50% [6].

However, under dynamic seismic loading, the relationship between stiffness and drift is nonlinear. While semi-rigid frames generally display lower lateral stiffness, they do not always experience greater peak displacements than rigid frames. Some studies using time-history analysis found that, under specific ground motion records, the top displacements in properly designed semi-rigid frames were lower than those in rigid counterparts owing to period elongation and energy attenuation through hysteretic damping in the connections [14]. Conversely, other studies note that while base shear decreases with reduced stiffness, lateral drift typically increases, suggesting that an optimum stiffness exists to balance force reduction and drift control [16,20]. Based on the literature reviewed, the rigidity factor represents the direct ratio of joint initial rotational stiffness to beam flexural stiffness ($R_{ki}L/EI$), which is then used to calculate the fixity factor ($r = 1/(1 + 3EI/R_{ki}L)$) to normalize the joint's rigidity on a scale from 0 to 1 [31,66]. According to Eurocode 3, semi-rigid connections fall strictly within the range of fixity factors from 0.14 to 0.89 [67]. In practical applications, such as extended end-plate connections, fixity factors ranging from 0.5 to 0.7 are commonly reported as the optimal target [68]. Designing within this range

successfully balances a reduction in base shear—which allows for lighter, more economical beam and column sections—with appropriately controlled inter-story drift. This optimal fixity corresponds to an initial rotational stiffness of approximately 5-15 EI/L, bridging the flexible and stiff semi-rigid classifications [69]. Designers are encouraged to initiate the optimization process with a fixity factor of 0.66; at this value, the maximum moment at the beam ends equals half the mid-span moment of an ideally pinned beam, providing a practical starting point for the most economical structural profile [17]. If the increased inter-story drift inherent to semi-rigid frames exceeds allowable limits, the literature suggests designers can effectively mitigate this by introducing lateral bracing systems (such as zipper columns or steel plate shear walls) while still maintaining the economic benefits of the semi-rigid beam-to-column joints [68].

5.2. Internal Force Redistribution

Semi-rigid connections facilitate the redistribution of internal forces, a behavior that differs significantly from that of rigid frames. In rigid frames, peak bending moments typically concentrate at the beam ends (hogging moments). Introducing semi-rigidity allows for relative rotation at the joint, which reduces these end moments and transfers a portion of the load to the mid-span (increasing sagging moments) [4]. This redistribution mechanism allows designers to optimize beam sections, likely reducing steel weight and utilizing the member's capacity more efficiently [34,70].

However, this pliability can adversely affect columns in unbraced frames. As connection restraint decreases, the effective length of columns may increase, and the frame's stabilizing "triangular action" is diminished, potentially leading to higher column moments due to secondary effects [2].

5.3. Elastic Critical Loads and Stability

The stability of steel frames is fundamentally connected to connection stiffness, which exerts both qualitative and quantitative effects on the overall structural response. Qualitatively, the failure characteristics differ markedly between frame types. As frames approach their critical state, rigid frames tend to exhibit rapid stiffness degradation, as evidenced by sharp breaks and slope changes in their load-lateral displacement curves [71]. In contrast, semi-rigid frames exhibit a gradual, continuous reduction in stiffness as they approach instability. Quantitatively, finite element analyses indicate that the elastic critical load of a steel frame is significantly reduced when connection flexibility is introduced. For example, numerical studies show that switching from rigid to semi-rigid connections can reduce the elastic critical load by approximately 54% to 60%; in verified models, the critical load dropped from 3350.1 kN to 1345.4 kN for a two-story frame and from 1793.3 kN to 821.3 kN for a three-story frame [71]. Therefore, particularly in unbraced frames, the inclusion of semi-rigid behavior is fundamental for accurate stability assessment, as neglecting joint flexibility results in a severe quantitative overestimation of the frame's buckling capacity [70].

5.4. Performance in Progressive Collapse and Catenary Action

In progressive collapse scenarios, such as the sudden loss of a primary column, local equilibrium must be maintained by transferring the load to adjoining beams, requiring the structural joints to provide adequate axial constraint to develop catenary actions [52]. Bolted extended-end-plate connections are widely recommended in anti-collapse design because they can provide the necessary load resistance and rotational capacity to establish this secondary anti-collapse mechanism [44,45]. Under the large deformations required to sustain these catenary actions, the joints undergo significant geometric nonlinearity. As the displacements exceed the normal bolt-hole gaps, the connection transitions from flexural

behavior to resisting extreme axial tension, activating substantial membrane forces in the end-plate and intense shear and tensile forces in the connecting bolts [52].

5.5. Application in Specialized Systems

The literature illustrates the application of semi-rigid connections in several specialized structural systems:

- Braced frames: In braced frames, where diagonal members provide lateral stability, semi-rigid connections are often more economical than rigid ones. They allow optimization of beam weights by balancing mid-span and end moments, while the bracing system controls drift that would otherwise be exacerbated by connection flexibility [33,34]. In steel X-braced reinforced concrete frames, varying the connection stiffness was found to considerably influence stress distributions inside the braces, even while global displacements remained largely unaffected [3].
- Steel plate shear walls (SPSW): Systems combining semi-rigid frames with steel plate shear walls inherit the ductility of the connections and the stiffness of the walls. Research indicates that in such systems, the SPSW undertakes 70–80% of the overall lateral load, allowing the semi-rigid frame to function primarily as a gravity and back-up system that lessens the "strong-column weak-beam" design challenges [16,33].
- Trusses and industrial buildings: Semi-rigid connections are widely used in industrial buildings, particularly for nodes connecting open-web tapered sections to solid sections [2]. In tubular steel trusses, welded joints often behave semi-rigidly rather than as ideal pins; accounting for this rotational stiffness affects the buckling lengths of truss members and may lead to cost savings versus traditional pinned assumptions [72].

6. Seismic Behavior and Cyclic Loading Response

The seismic performance of steel frames is inherently connected to the dynamic characteristics of their beam-to-column connections. Under earthquake loading, semi-rigid joints undergo large inelastic deformations, exhibiting complex hysteretic behavior that governs the structure's energy-dissipation capacity and global stability.

6.1. Dynamic Response Characteristics and Hysteresis Behavior

The cyclic response of semi-rigid connections is commonly characterized by "pinched" hysteresis loops, a phenomenon resulting from the opening and closing of gaps among connection components, bolt slippage, and ovalization of bolt holes [14,73].

The degree of pinching and the shape of the hysteresis loops depend heavily on the connection topology. For instance, connections using angles (e.g., top-and-seat angles) or T-stubs often exhibit substantial pinching due to bolt slip and local yielding. In contrast, extended end-plate connections—particularly those with thinner plates—tend to exhibit more stable, "broad" hysteresis loops with higher energy dissipation [9,14].

Under repeated loading, semi-rigid connections experience progressive stiffness degradation (softening) and strength deterioration. This degradation is often quantified using the secant stiffness, which decreases with increasing rotation amplitude [21,73]. Experimental studies indicate that stiffness degradation is most rapid during the initial loading cycles up to the yield point, after which it stabilizes as plastic deformations accumulate in the end-plates or angles [21,65].

6.2. Energy Dissipation and Low-Cycle Fatigue

Energy dissipation in semi-rigid frames is mainly achieved through the inelastic deformation of connection components (e.g., yielding of end-plates, angles, or column flanges) rather than the beam members themselves [16,33]. Properly designed semi-rigid

connections can act as "structural fuses," dissipating seismic energy through stable hysteretic damping while keeping the main structural members (beams and columns) largely elastic [19,74]. Figure 6 illustrates the hysteresis loops and energy dissipation.

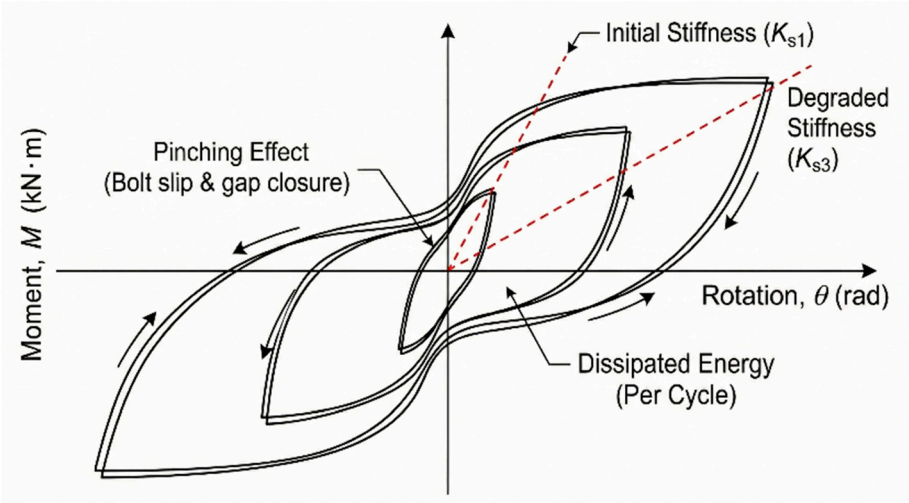


Figure 6. Diagram of energy dissipation.

However, this energy dissipation mechanism is limited by low-cycle fatigue. Repeated load cycles can lead to the accumulation of plastic strains, eventually causing fracture in bolts or welds [2]. Research results show that specimens subjected to successive loading display lower rotation and moment capacities than those under monotonic loading due to low-cycle fatigue [36]. To reduce premature failure, design protocols frequently aim to ensure failure occurs via ductile yielding of the plate components rather than brittle fracture of the bolts [2,36].

6.3. Effect on Global Seismic Response

The rotational stiffness of joints significantly changes the dynamic properties of the structural system. Introducing semi-rigidity increases the fundamental natural period of the frame compared to a fully rigid model [14,20]. This period elongation typically shifts the structure into a region of the response spectrum with lower spectral accelerations, consequently reducing the total base shear demand [19,20].

Although reduced stiffness lowers base shear, it can simultaneously increase inter-story drifts. However, the relationship is nonlinear; some studies indicate that increased damping from hysteretic connection behavior can compensate for stiffness loss, resulting in drift values comparable to or even lower than those of rigid frames under certain ground motions [14,74]. Conversely, other research suggests that as connection rigidity decreases (e.g., from 100% to 60%), peak story accelerations may increase due to the complicated interaction of higher modes and structural flexibility [20].

The local flexibility of semi-rigid connections—the partial ability of joints to rotate without being fully rigid—influences the dynamic parameters (such as natural frequencies and mode shapes) of the entire frame. Kasimzade et al. [75] demonstrated that experimental modal analysis (EMA), a technique where a structure's vibrational response is measured under real or simulated conditions, can effectively capture the dynamic characteristics of steel structures using ambient vibration recordings. Tuhta et al. [76] showed that temperature variations significantly affect experimental modal parameters and the evaluation of stiffness (the resistance of a structure to deformation) in steel frameworks. Günday and Tuhta [77] investigated the dynamic effects of central X-bracing (cross-shaped reinforcements at joint points) in steel structure models, demonstrating how global frame

stiffness changes with structural modifications. Günday [78] employed SSI-COV (Stochastic Subspace Identification with CoVariance), a method for identifying system dynamics, for structural health monitoring (continuous assessment of integrity) of steel models, bridging theoretical connection behavior with real-time identification. Günday [79] explored the effects of Nano-TiO_2 (nanoparticle titanium dioxide) coating on light steel container houses using OMA (Operational Modal Analysis, which monitors vibrations under normal usage), providing insights into how material innovations influence dynamic parameters. Collectively, these studies underscore the critical link between local joint flexibility and global structural dynamics, suggesting the need for further integration in future research on semi-rigid connections.

6.4. Response Modification Factors

The energy dissipation capacity of semi-rigid connections justifies the use of specific response modification factors (*R*-factors) in seismic design. The *R*-factor accounts for the structure's ductility and overstrength, allowing design forces to be lower than those required for elastic response [69]. Semi-rigid frames commonly display greater overstrength and ductility reserves than nominally pinned frames, permitting larger *R*-factors. Studies on intermediate moment-resisting frames suggest that semi-rigid configurations (e.g., 60–70% rigidity) can increase the likelihood of meeting performance levels, such as "Collapse Prevention," compared to rigid frames, due to their ability to redistribute forces and dissipate energy through connection plasticity [19,20]. Consequently, ignoring connection flexibility may result in inaccurate estimations of the *R*-factor and potential overdesign or underestimation of safety margins.

6.5. Seismic Prequalification and the EQUALJOINTS Projects

To ensure reliable seismic performance and adequate energy dissipation in steel frames, standardized prequalification procedures for beam-to-column joints are critical. While such procedures have been established in North America and Japan, the European EQUALJOINTS and EQUALJOINTS-Plus projects were specifically developed to introduce European seismic prequalification criteria for a variety of standardized joints, including extended stiffened and unstiffened bolted end-plate connections [80].

These research initiatives emphasized applying the hierarchy of resistances among the joint macro-components (the beam, the connection, and the column web panel) to strictly control the joint's failure mode [80,81]. Depending on the intended seismic performance and the structural system (e.g., moment-resisting or dual frames), end-plate joints within the EQUALJOINTS framework are classified into three design objectives:

Full-strength joints: Designed to enforce plastic hinge formation solely in the connected beam, preserving the connection and column web panel in the elastic range [51,63,80].

Equal-strength joints: Designed to promote a balanced yielding mechanism, where plastic deformations are shared between the beam and the connection (e.g., the end-plate in bending) [51,81]. This shared dissipation reduces construction costs and limits the concentration of severe damage in the beam.

Partial-strength joints: Designed to concentrate plastic deformations primarily in the connection and/or the column web panel, often used to provide redundancy and extra dissipation capacity in dual frames [51,82].

Experiments and simulations showed that well-designed extended end-plate connections—both stiffened and unstiffened—have stable, rounded hysteretic loops without significant strength loss [53]. These joints meet the requirements of Eurocode 8 for inter-story drift and plastic rotation in ductile structures. Designers can use an updated

"cyclic component method" to predict moment–rotation response and energy dissipation under cyclic loading [80].

Recent work based on the EQUALJOINTS framework evaluated these joints under large rotations and optimized their geometry [52]. Using rib stiffeners and non-symmetric octagonal bolt arrangements improves stress distribution among bolts. These configurations create full-strength joints with thinner end plates and smaller connections than in traditional designs [63].

7. Synthesis and Research Gaps

The body of research on semi-rigid connections shows a clear consensus that they can optimize steel-frame design by balancing stiffness, strength, and ductility. However, a critical synthesis of the existing studies reveals substantial disparities between advanced research capabilities and practical design implementation, as well as specific gaps in testing and modeling that remain unaddressed.

7.1. Synthesis of Key Findings

Researchers consistently show that modeling connections as semi-rigid, rather than as idealized rigid or pinned, yields more realistic predictions of frame behavior. Studies show that semi-rigid connections facilitate moment redistribution, enabling reduced beam sizes and overall frame weight [1,4]. While this pliability increases lateral drift, it simultaneously elongates the fundamental period of the structure, perhaps reducing seismic base shear demands [19,20].

However, there is a divergence in findings regarding the optimal degree of stiffness. While some studies suggest that decreasing stiffness improves seismic performance by acting as a "structural fuse" to dissipate energy [74], others advise that excessive flexibility may lead to P-Delta instability and increased inter-story drifts, potentially violating serviceability limits [2,6]. Furthermore, although finite element methods have proven effective in depicting global moment–rotation (M-θ) behavior, inconsistencies remain in predicting localized failure modes, such as tearing of column perforations in rack systems or specific bolt fractures under dynamic loading, which are often due to simplified contact or boundary-condition assumptions [44,60].

7.2. Restrictions in the Current Design and Modeling

Despite the maturity of the field, multiple constraints impede the extensive adoption of semi-rigid design in practice:

- **Disconnect between analysis and design:** Current design workflows are inherently iterative and inefficient. Designing semi-rigid frames typically requires a "forward" approach in which joint details are assumed to calculate frame stiffness, followed by a computationally demanding verification process [31]. Although optimization algorithms such as Genetic Algorithms and Biogeography-Based Optimization have been proposed to automate this process, they are resource-intensive and have not yet been integrated into standard commercial design software [18,83].
- **Simplified constitutive models:** Practical design tools commonly rely on linearized or bilinear springs (e.g., the half-initial secant stiffness method) to represent complex nonlinear connection behavior. These simplifications do not capture stiffness degradation from cyclic loading or the "pinched" hysteresis loops caused by bolt slippage, resulting in inaccuracies in predicting dynamic response [67,71].
- **Lack of standardization for existing structures:** There is a considerable lack of established procedures for assessing the reliability of non-standard or legacy connections, such as top-angle and seat-pad connections found in older high-rise buildings. Current

codes do not adequately cover the performance of these riveted or hybrid connections, forcing engineers to rely on costly experimental testing [84].

7.3. Research Gaps

Future research efforts must tackle particular deficiencies in test coverage and modeling sophistication:

- **Dynamic and impact loading:** While static behavior is well documented, experimental data on the performance of bolted joints under high-strain-rate impact loading are scarce. Current studies struggle to accurately measure impact forces and stress fields during dynamic events, limiting the validation of numerical models for accidental loading cases [44].
- **3D behavior and multi-axial loading:** The vast majority of research focuses on 2D in-plane bending. There is an essential need for experimental and numerical studies of 3D joint behavior that explicitly examine the interactions among major-axis bending, minor-axis bending, and torsion. The effects of biaxial loading and the contribution of floor slabs or transverse beams to joint stiffness are often neglected [55,67].
- **New materials:** As the use of stainless steel grows, there is a significant lack of full-scale experimental evidence regarding the moment–rotation behavior of stainless steel beam-to-column connections. Existing databases are based on carbon steel, and failure modes in stainless steel connections may change due to its high ductility and strain-hardening characteristics [37].
- **Fire and thermal interaction:** Although not the primary focus of all studies, the behavior of semi-rigid joints under fire conditions and their influence on beam catenary action remain areas that warrant further investigation to enhance structural strength [2].

8. Conclusions and Recommendations

8.1. State-of-the-Art Summary

The traditional structural engineering practice of idealizing beam-to-column joints as either perfectly rigid or perfectly pinned is increasingly acknowledged as an oversimplification. Extensive experimental and numerical research has shown that the actual behavior of most practical connections, particularly bolted types, is semi-rigid and governed by a nonlinear moment–rotation (M-θ) relationship. Among these, the extended end-plate connection is frequently used for its ability to transmit significant moments, excellent constructability, and high relative stiffness.

Recognizing and precisely modeling this semi-rigidity provides considerable benefits. Economically, it facilitates redistribution of internal moments, allowing optimized beam and column sections that reduce the steel frame's total weight. Structurally, semi-rigid connections act as essential sources of damping; their flexible, hysteretic behavior lengthens the structure's natural period, reduces seismic base shear demands, and provides vital energy reduction. Beyond conventional damping, the state of the art has recently shifted toward resilience-based design, prioritizing post-earthquake reparability and minimizing residual drift. Modern semi-rigid connections are increasingly conceptualized as "structural fuses" that concentrate plastic damage in easily replaceable components while protecting the main structural members. Innovations such as replaceable double T-stubs made of low-yield-point steel, as well as self-centering connections equipped with post-tensioned strands or shape-memory alloys (SMAs), represent a major leap forward in mitigating permanent deformation after severe seismic events. To capture these elaborate interactions—such as end-plate yielding, bolt elongation, prying actions, and self-centering mechanisms—the industry relies heavily on sophisticated 3D nonlinear FE modeling and the analytical

component method. Despite these advancements, the widespread practical application of semi-rigid frames remains hindered by the complexity of predicting connection stiffness, reliance on simplified linear models in commercial software, and a scarcity of standardized procedures for legacy structural examinations.

8.2. Recommendations for Engineers and Researchers

Based on the synthesized literature, the following actionable recommendations are presented:

- **Transition to inverse design workflows:** Structural designers should shift from labor-intensive, iterative "forward design" approaches to performance-based "inverse design" methodologies. By treating the joint as an abstracted performance parameter (the end fixity factor) and using optimization algorithms, such as genetic algorithms, engineers can greatly accelerate the design process. It is recommended to use an initial fixity factor of 0.66 as a starting point to target the most economical profile balance.
- **Integrate with advanced bracing in seismic zones:** When designing high-rise or tall steel buildings in near-fault areas, engineers should utilize semi-rigid connections in combination with advanced lateral bracing systems. Specifically, incorporating zipper columns into Chevron bracing integrates structural performance among stories, controls massive lateral displacements under large deformations, and improves overall structural ductility.
- **Adopt resilience-based design and structural fuses:** To enhance post-earthquake reparability, designers should implement connection typologies that act as replaceable "fuses"—such as low-yield-point steel connections—which intentionally concentrate damage away from main structural members. Furthermore, to prevent structures from becoming irreparable due to permanent displacements, the integration of self-centering technologies, such as post-tensioned high-strength strands or SMA ring springs, should be prioritized.
- **Expand research into 3D and multi-axial loading:** Future studies must move beyond the current reliance on 2D in-plane bending tests. Researchers should focus on experimental and numerical investigations of 3D joint behavior, particularly examining the complex interactions among major-axis bending, minor-axis bending, and torsion. Additionally, the contributing stiffening effects of floor slabs and transverse beams must be explicitly modeled and tested.
- **Investigate dynamic impacts and new materials:** There is an essential need to generate full-scale experimental data on the performance of bolted joints under high-strain-rate impact loading to validate FE models for accidental loading cases. Furthermore, experimental databases must be expanded to include connections manufactured from stainless steel; its high ductility and strain-hardening characteristics are likely to yield failure modes that differ significantly from those traditionally observed in carbon steel.

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Abbreviations

The following abbreviations are used in this manuscript:

EEP	Extended end plate
AISC	American Institute of Steel Construction
FR	Fully restrained
PR	Partially restrained
CM	Component method
BSEP	Bolted stiffened end plate
BFP	Bolted flange plate
FEM	Finite element method
SPSW	Steel plate shear walls

Appendix A

We reviewed over 100 sources on semi-rigid connections, with a focus on extended-end plate joints, and synthesized the research findings in Table A1. Table A1 is organized by paper topics: seismic analysis, connection classifications, modeling approaches, and design code evaluation. Within each topic, entries are listed in reverse chronological order to highlight the latest developments.

Table A1. Summary of previous studies on seismic performance of steel structures with semi-rigid connections.

Title	Authors	Key Findings	Topic	Remarks
Impact of carbon fiber-reinforced polymer sheets and bolt diameter on the seismic performance enhancement of steel beam-column joints	Fayiz et al. 2025 [85]	Applying CFRP sheets to the backside of end plates increases bolt tension capacity by 1.2 to 1.3 times. Larger bolts yield higher ultimate capacities and reduced deformation at failure.	seismic analysis	The application of CFRP significantly increases bolt tension capacity by 1.2–1.3 times, thereby reducing the risk of bolt failure.
Nonlinear seismic performance assessment of energy-based steel structures with semi-rigid connections	Ardalani and Aydin, 2025 [86]	Semi-rigid structures show a 93.67% greater energy dissipation capacity compared to rigid structures. Both rigid and semi-rigid structures remained at the Immediate Occupancy level.	seismic analysis	The energy-based analyses show that the semi-rigid structure has a greater energy dissipation capacity (93.67%) than the rigid one.
Evaluation of the seismic performance of tall steel frames with semi-rigid connections with a zipper bracing system	Amir et al., 2023 [87]	Zipper columns in Chevron braces effectively control relative story displacement. Semi-rigid connections are more efficient in dissipating seismic energy in near-fault areas.	seismic analysis	The presence of zipper columns in Chevron braces has enabled integrated frame performance throughout the structure's height.

Table A1. *Cont.*

Title	Authors	Key Findings	Topic	Remarks
Cyclic and monotonic performance of stiffened extended end-plate connections with large-sized bolts and thin end-plates	Yasin Onuralp Özkılıç, 2022 [36]	AISC and EC3 provisions significantly underestimate the moment resistance of stiffened extended end-plate joints. The ratio of actual to predicted plastic resistance averaged 2.31 (AISC) and 2.77 (EC3).	seismic analysis	The results indicated that the moment resistance of stiffened extended end-plate joints is underestimated by the current provisions.
On the seismic evaluation of steel frames laterally braced with perforated steel plate shear walls considering semi-rigid connections	Majlesi et al., 2022 [16]	Maximum story acceleration and base shear significantly decrease (by up to 27.7% and 18.8%, respectively) due to reduced capacity of semi-rigid connections and increased perforation diameter in SPSWs.	seismic analysis	By using a semi-rigid connection in an adjacent span to the SPSW, the flexural capacity at the beam end decreases, thereby enhancing structural performance with respect to the strong-column–weak-beam criterion.
Experimental and numerical research on the multi-stage seismic failure modes of a steel frame with an end-plate connection	Lu et al., 2021 [41]	The seismic failure sequence was as follows: end-plate yield, beam-end yield, column-base buckling, and, finally, whole-frame failure. This order satisfies the 'strong column weak beam' design criteria.	seismic analysis	The failure order of the specimen was the yield of the end-plate, which indicated that the specimen satisfied the design criteria of 'strong column weak beam'.
Seismic performance evaluation of steel frame structure considering semi-rigid connections	Koirala and Suwal, 2020 [4]	Semi-rigidity increases lateral displacement and mid-span moment. Ductility increases with reduced connection rigidity, enhancing seismic performance by reducing earthquake force magnitudes.	seismic analysis	The seismic performance of the structure was improved by reducing the rigidity of the connections.
Seismic behavior of semi-rigid steel joints—Major axis T-stub and minor axis end-plate	Shi et al., 2019 [43]	The proposed joint with the major-axis T-stub and the minor-axis end plate showed improved bending resistance and energy dissipation. Failures occurred in the T-stub or the end plate, making them easy to repair.	seismic analysis	The major beams failed with T-stub fractures, and the minor beams failed with substantial bending deformations at the end-plates, which are easy to repair.
Dynamic response characteristics of steel portal frames having semi-rigid joints	Bhatti, 2017 [88]	The natural frequency decreases with reduced connection stiffness. Extreme increases in input acceleration can cause the connection stiffness to drop to near zero, thereby increasing the response spectra.	seismic analysis	The natural frequency of the frame decreases as connection stiffness decreases, and the resonant frequency decreases in increments of a_i.

Table A1. *Cont.*

Title	Authors	Key Findings	Topic	Remarks
Seismic Design of Bolted Connections in Steel Structures—A Critical Assessment of Practice and Research	Tiago et al., 2022 [89]	The scientific literature on this topic spans approximately 25 years, with over 400 articles, primarily journal articles (68–75%), while review articles account for less than 1%. The research output is highly concentrated among a few research groups. Eurocode 8 is expected to enter a fourth generation with developments in pre-qualified joints, but shifting to a full performance-based design philosophy will significantly increase design complexity.	seismic design	The paper serves as a systematic review to fill the gap in this niche, focusing mainly on the 2016–2021 period. It evaluates design philosophies and research trends and provides insights for future developments, such as additively manufactured products for steel connections.
Seismic performance of semi-rigid connection of food warehouses' steel frame	Han and Wang, 2016 [90]	Increasing the structural mass in semi-rigid frames increases bearing and deformation capacities, thereby improving seismic performance, though the influence of interlayer shear is minimal.	seismic analysis	Increasing the mass of the steel frame can enhance the structure's load-bearing and deformation capacities, thereby improving its ability to dissipate seismic energy.
The design and seismic performance of low-rise long-span frames with semi-rigid connections	Aksoylar et al., 2011 [14]	Using energy-dissipative semi-rigid connections can eliminate the need for strong-column weak-beam requirements and reduce structural steel weight by up to 25% (column weight).	seismic analysis	By designing low-rise, long-span structures with energy-dissipative zones in semi-rigid or partial-strength connections, most of the aforementioned shortcomings can be eliminated.
Finite element analysis of prefabricated semi-rigid concrete beam–column joint with steel connections	Xiao et al., 2024 [91]	A new prefabricated joint using steel sections and bolts showed a 31.7% increase in ultimate load capacity and a 7.23% increase in ductility compared to traditional cast-in-place concrete joints.	connection types	The newly combined joint exhibited a substantial 31.7% increase in its ultimate load-carrying capacity.
Semi-rigid behavior of stainless steel beam-to-column bolted connections	Mahmud et al., 2021 [37]	TSA and TS-DWA connections meet FEMA ordinary moment frame rotation requirements of 30 mrad. Stainless steel ductility ensures high rotational capacity.	connection types	The extensive ductility of stainless steel ensured that all three connection types achieved a minimum connection rotation of 30 mrad.
Strength of extended stiffened end-plate bolted joints: Experimental and numerical analysis	Gašić, et al., 2021 [62]	Rib stiffeners reduce end-plate deformations and increase stiffness/moment resistance (17.5 kNm stiffened vs. 13.6 kNm unstiffened), but lead to a reduction in connection ductility.	connection types	The stiffening of the end-plate results in a significant increase in the moment-resisting capacity and initial stiffness, but reduces the connection's ductility.

Table A1. *Cont.*

Title	Authors	Key Findings	Topic	Remarks
An overview of the connection classification index	Faridmehr et al., 2019 [33]	Eurocode 3 provides a more reliable classification index than AISC 360-10. Experimental results showed that bolt size and end-plate thickness have a negligible influence on the initial rotational stiffness of EEP connections.	connection types	Beam-to-column connections are semi-rigid; therefore, such behavior should be included in the analysis and design methods.
The influence of rib stiffeners on the response of extended end-plate joints	Roberto et al., 2018 [61]	Rib thickness largely influences moment–rotation response by shifting the center of compression from the beam flange to the rib web, increasing the internal lever arm.	connection types	The thickness of the stiffener largely influences the moment–rotation response of the joints.
Simple joints to Eurocode 3 (Publication P358)	Nunez et al., 2014 [92]	Standard connections are considered nominally pinned if the design moment resistance is less than 25% of the full-strength joint moment. Fin plate rotational capacity relies on hole distortions and bolt shear.	connection types	Joints designed in accordance with the principles within this publication can be classed as nominally pinned without calculation.
Simple joints to Eurocode 3—Section 4.2 End Plates	Nunez et al., 2014 [92]	Full-depth end plates offer higher tying resistance than partial-depth end plates. In S275 steel, plates thicker than 12 mm may fail to satisfy the rotation capacity required for nominally pinned classification.	connection types	In S275 steel, end plates thicker than 12 mm do not satisfy Eurocode requirements for rotation capacity.
Investigations on the behavior of semi-rigid endplate connections	Arul et al., 2009 [40]	Stiffness increases with plate thickness and reduces as the lever arm increases. Load capacity decreases with increased bolt spacing due to prying action. The Frye-Morris model often overestimates stiffness.	connection types	It is concluded that the Frye-Morris model does not represent the different stiffness ranges in the endplate connection.
Behavior of extended end-plate moment connections subject to cyclic loading	Sumner and Murray, 2002 [35]	Four-bolt configurations are limited by bolt capacity to less than half of the beam sections; strength can be increased by adding stiffeners or by increasing the number of bolts.	connection types	End-plate moment connections can provide economical solutions for rigid-frame construction. Their use is not presently recommended in areas of high seismic activity.
Unification of flush end-plate design procedures	Hendrick, 1985 [93]	Unified design equations based on yield-line theory. Stiffeners outside tension rows increase strength by approximately 20% compared to unstiffened configurations.	connection types	The results from the preceding yield-line analyses adequately predict the failure moment for the two-bolt, four-bolt, and four-bolt stiffened flush end-plate configurations.

Table A1. *Cont.*

Title	Authors	Key Findings	Topic	Remarks
Structural performance of semi-rigid beam-to-column connections in steel storage racks	Mirjana et al., 2026 [60]	Key parameters include connector class, column thickness, and beam height. Rotational stiffness in FEM can vary by up to 23% from experimental results.	modeling methods	Validated FEM analysis emerges as a dependable and cost-effective alternative to experiments.
The analysis and design of semi-rigid connections in steel structures	Aydin, 2025 [2]	Semi-rigid connections bridge the gap between rigid and pinned types, aiding energy dissipation. Rigid connections are defined as having stiffness $\geq$0.8 times nominal stiffness.	modeling methods	Semi-rigid joints demonstrate superior performance to both fully rigid constructs and simple connections in managing loads effectively.
A novel interval matrix stiffness method for the analysis of steel frames with uncertain semi-rigid connections	Federica and Alba Sofi, 2024 [67]	Developed an interval matrix stiffness method using fixity factors to account for connection stiffness uncertainty, requiring only two deterministic analyses to estimate response bounds.	modeling methods	The interval model allows the analyst to select a reference connection type and describe the uncertainty in the actual connection.
A design method for semi-rigid steel frames via pre-established performance-based connection database	Yin et al., 2022 [31]	The frame design is transformed to match performance requirements between elements and connections by using discrete fixity-factor intervals of 0.025, reducing the number of design variables.	modeling methods	The frame design is transformed into the task of finding an appropriate match between the performance requirements of elements and connections.
Semi-rigid connections in steel structures: State-of-the-Art report on modeling, analysis and design	Celik and Sakar, 2022 [94]	Joints behave as either perfectly rigid or pinned. Including actual semi-rigid behavior in analysis provides significant economic advantages.	modeling methods	While many connections considered rigid rotate a little under load, this case is defined as a semi-rigid joint.
Parametric analysis and stiffness investigation of extended end-plate connection	Liang et al., 2020 [54]	Panel-zone shear is the primary factor affecting connection stiffness, accounting for 2/3 of total rotation. FE results showed an average difference of 8.99% from the proposed calculation model.	modeling methods	Parametric studies show that the panel-zone shear force is the key factor and significantly affects the connection stiffness.
A comparative study of AISC360 and EC3 provisions for member stability	Ömer, 2016 [95]	Direct Analysis Method (DM), Effective Length Method (ELM), and EC3 yield similar axial capacities. ELM generally results in smaller moment capacities. ELM uses K factors while DM assumes K = 1.	modeling methods	ELM uses the effective length factor (K), which depends on the support and side-sway conditions. On the other hand, DM assumes the effective length factor K = 1.
Stability analysis of steel frames with semi-rigid connections and rigid zones by using the P-Delta effect	Anh, 2002 [96]	Secondary moments (P-Δ effects) must be considered in steel structures; compressive axial forces make structures more flexible against lateral loads, leading to potential buckling.	modeling methods	Secondary moments (P-Δ effects) must be considered in steel structures because their members are less rigid than concrete.

Table A1. *Cont.*

Title	Authors	Key Findings	Topic	Remarks
Semi-rigid frame design methods for practicing engineers	Christopher and Bjorhovde, 1999 [34]	Proposed a linearized connection stiffness method for first-order analysis. Economy in semi-rigid frames results from reduced beam moments and increased restraint at column ends.	modeling methods	The economy of semi-rigid frames is the result of reduced beam moments, reduced beam deflections, and increased restraint at column ends.
The stiffness model of revised annex J of Eurocode 3	Weynand et al. 1996 [97]	Developed a model for rotational stiffness based on the component method, assuming a fixed ratio of 3 between initial stiffness and secant stiffness for end-plated joints.	modeling methods	The essence of this method is that the mechanical properties of its components determine the joint's rotational response.
Inelastic finite element analysis of stiffened end-plate moment connections	Ghassemieh et al., 1983 [98]	Presented finite element/regression analysis equations to predict bolt forces above pretension level, including inelastic material properties for A36 steel and A325 bolts.	modeling methods	A sensitivity study utilizing finite element analysis on various geometric and force-related variables yielded regression equations for end-plate deformation and bolt tension.
Limit design of extended end-plate connections	Mann and Morris, 1979 [99]	Identified three failure modes for column flanges: bolt rupture without prying, combined bolt fracture and flange yielding, and yield lines causing double curvature.	modeling methods	If the first failure mode governs, the total bolt force equals the applied flange force.
A fresh look at bolted end-plate behavior and design	Krishnamurthy, 1978 [100]	Prying forces are ignored in the design procedure for four-bolt extended unstiffened end plates for service load conditions, as prying formulas are overly conservative.	modeling methods	If a prying action is present, it is overly conservative to assume it acts at the edge of the plate, as this typically results in end plates thicker than necessary.
A comparative study of AISC-360 and EC3 strength limit states	Cem and Sahin, 2011 [101]	Nominal capacities are generally close, but differences exist for flexure in I-sections with non-compact flanges and bearing strength at bolt holes.	design code comparison	In general, both specifications provide nominal capacities that are close to each other. Significant differences were reported for some limit states.

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