

Article

A Component-Based Joint Model for Nonlinear Analysis of Bolted Extended End-Plate Connections

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Abstract

Semi-rigid connections play a critical role in steel structures; however, most existing component-based approaches do not explicitly account for stiffness degradation and post-yield residual stiffness, which may reduce the accuracy of moment–rotation predictions. To address this limitation, direct numerical simulations (DNSs) of representative T-stub beam-to-column joints were conducted to investigate their nonlinear rotational behavior. Based on the observed joint response, a Joint Component Model (JCM) capable of representing sequential yielding, stiffness evolution, and residual rotational stiffness was developed. Constitutive relationships were derived, and a parameter identification procedure directly relating joint geometry and component mechanical properties to the model parameters was established. The proposed model was subsequently implemented in ANSYS and validated through analyses of T-stub joints and steel frames subjected to static and dynamic loading. The results showed good agreement between the JCM and DNS in terms of moment–rotation relationships, force–displacement responses, and dynamic time-history responses. Compared with DNS, the proposed model significantly reduced computational time while maintaining satisfactory prediction accuracy. The proposed JCM therefore provides an efficient and reliable component-based modeling framework for modeling semi-rigid steel connections and capturing stiffness evolution throughout the entire joint rotation process.

Keywords: semi-rigid connection; component-based model; nonlinear analysis; Joint Component Model; steel structures



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1. Introduction

High-strength bolted connections are widely used in steel structures and commonly exhibit semi-rigid behavior, transmitting bending moments while allowing relative rotation between connected members. Although direct numerical simulation (DNS) can provide an accurate description of joint moment–rotation behavior, its computational cost is often prohibitive for frame-level analyses. Therefore, efficient yet accurate alternatives are needed to model the moment–rotation response of semi-rigid beam-to-column joints. Among various semi-rigid beam-to-column connections, bolted extended end-plate connections are widely used in steel structures due to their favorable structural performance and ease of fabrication, and they have been extensively studied in terms of their monotonic and seismic behavior [1,2].

Existing approaches for describing joint moment–rotation relationships can be broadly classified into two categories: empirical models and mechanical models.

(1) Empirical models.

These include linear [3,4], polynomial [5,6], and power-function models [7–9], as well as B-spline formulations [10,11] and four-parameter exponential models [12]. Such models are typically obtained by fitting experimental data. Linear, polynomial, and power-function models are suitable for preliminary analyses but generally have limited ability to capture nonlinear behavior over the full response range. B-spline and four-parameter exponential models can represent nonlinearity more effectively; however, they may suffer from numerical instability. In addition, B-spline models usually require extensive experimental datasets and involve higher computational complexity.

(2) Mechanical models.

This category includes plastic-hinge [13–15], transfer-matrix [16], viscoelastic [17–19], stiffness-matrix [20,21], multiscale finite element [22], and component-based methods [23]. Plastic-hinge and stiffness-matrix approaches enable efficient analyses by emphasizing plastic rotation and global stiffness, respectively. The transfer-matrix method is effective for multi-joint frame structures but depends strongly on parameter calibration. Viscoelastic and multiscale finite element models can capture complex nonlinear and dynamic responses; however, they introduce significant computational cost and parameter identification complexity.

Among mechanical approaches, the component method is the most widely adopted. In this method, each bolt row is idealized as an assembly of components characterized by axial stiffness and resistance, and the overall joint response is obtained by assembling these components.

Recent studies have extended the component method to estimate the initial rotational stiffness and yield/ultimate capacities of semi-rigid joints. Gil-Martín et al. [24] evaluated initial rotational stiffness using direct tensile spring stiffness functions, but the nonlinear post-yield response was not captured. Zhu et al. [25] predicted ultimate bending moments by modeling bolted connections as assemblies of nonlinear springs; however, stiffness degradation under combined bending and axial actions was neglected, leading to inaccuracies. Urbonas et al. [26–28] considered axial-force effects but did not address the influence of geometric configuration on stiffness evolution. Benedetto et al. [29] proposed a three-spring representation for CHS beam-to-column joints, but its applicability is restricted to specific connection types. Gusella et al. [30] developed a component-based theoretical model for arbitrary joints; nevertheless, it requires prior determination of joint strength and deformation characteristics. Zhou et al. [31] proposed the Generalized Component Method (GCM) to account for bolt interactions and shear-induced failure, but its implementation can be computationally demanding. Weynand et al. [32] developed a stiffness model that decouples stiffness prediction from strength calculations; however, residual stiffness was not considered. García et al. [33] proposed simplified stiffness formulations based on a modified Eurocode 3 component method, but significant errors were reported under high-load conditions.

In addition, several studies have represented joint constitutive behavior using discrete mechanical elements. Panel-zone behavior, which contributes to the overall rotational response of beam-to-column joints, has also been investigated using finite element analysis and analytical approaches [34]. Gil-Martín et al. [24] modeled panel zones using rotational springs to describe strength and stiffness. Zhou et al. [35] developed a spring model with transversely arranged bolt rows to represent combined tension–shear failure modes. Bučmys et al. [36] proposed a three-spring model for bolt groups and shear plates, but they

focused only on initial stiffness. Simões da Silva et al. [37] decomposed a bilinear spring for the column web under combined tension and shear, although both springs remained linear elastic. Shi et al. [38] modeled beam flange compression zones using rigid–plastic springs and other components using elastic–plastic springs. Simões da Silva et al. [39] proposed a component model for welded beam-to-column joints with beams of unequal depth, but its applicability was mainly limited to asymmetric welded joint configurations.

Building upon these studies, Liu et al. [40] proposed a moment–rotation model for semi-rigid beam-to-column joints using discrete mechanical elements to represent nonlinear rotational behavior. However, the model relies on calibration against experimentally obtained moment–rotation curves, and it therefore does not enable the direct determination of parameters from joint geometry and component mechanical properties.

In summary, existing component-based and simplified mechanical models primarily focus on predicting joint stiffness and resistance or on reproducing moment–rotation behavior through parameter calibration. The evolution of rotational stiffness during loading is often not explicitly represented, and model parameters frequently require calibration against experimentally obtained moment–rotation curves. Moreover, when joint mechanical models are constructed using spring components, standardized assembly procedures are often lacking. In particular, stiffness degradation and post-yield residual rotational stiffness are commonly neglected.

To address these limitations, this study proposes a Joint Component Model (JCM) for nonlinear analysis of bolted extended end-plate connections. The JCM establishes direct relationships between joint geometry, component mechanical properties, and model parameters, enabling direct parameter determination without calibration from experimental moment–rotation curves. In addition, the JCM integrates component behavior into a unified formulation that captures sequential yielding and stiffness evolution of bolt-row-related components throughout the loading process. Residual rotational stiffness is incorporated in a consistent manner to represent post-yield behavior and to ensure stable and efficient finite element implementation using standard spring and spring–slider elements.

Section 2 presents finite element–based direct numerical simulations (DNSs) of bolted extended end-plate beam-to-column connections to investigate their nonlinear rotational behavior. Section 3 develops the Joint Component Model (JCM), derives its constitutive relationships, and establishes parameter identification procedures. Section 4 implements the proposed model for bolted extended end-plate beam-to-column connections and steel frames under static and dynamic loading and evaluates both prediction accuracy and computational efficiency.

2. Investigation of the Rotational Behavior of Beam-to-Column Semi-Rigid Joints

2.1. Finite Element Model of the Joint

2.1.1. Geometric Model

Specimen SC6, selected from [41], is used for analyzing beam-to-column semi-rigid joints. A refined finite element model of specimen SC6 is created for the investigation.

The specimen consists of H-shaped Q345 steel beams and columns, as shown in Figure 1. The beam has a span of 1200 mm, and the column height is 2000 mm. The column cross-section is 300 mm × 250 mm × 8 mm × 12 mm, and the beam cross-section is 300 mm × 200 mm × 8 mm × 12 mm. Local thickening is applied to the column flanges within 100 mm of the end-plates, with the thickness matching the end-plate thickness. The connection bolts are M24 high-strength friction-grip bolts (Grade 10.9).

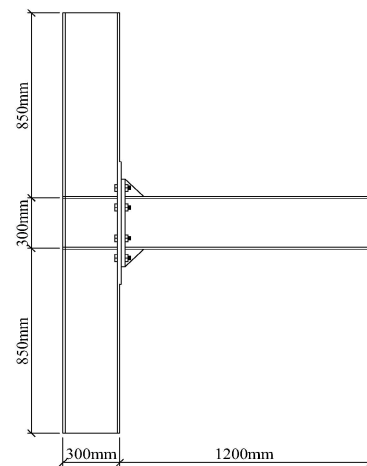


Figure 1. Geometry of specimen SC6.

2.1.2. Material Model

Q345 steel is represented by a four-linear kinematic hardening constitutive model, while high-strength bolts are modeled using a three-linear elastic–plastic constitutive model. The corresponding stress–strain curves are shown in Figure 2.

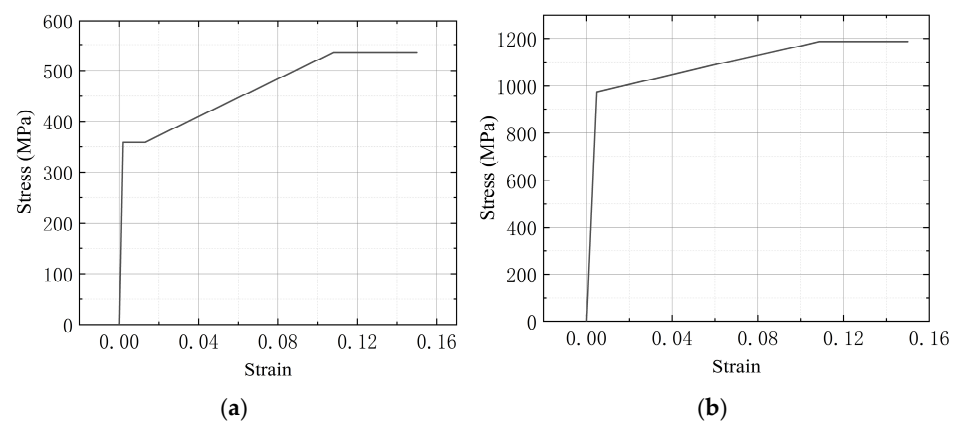


Figure 2. The stress–strain curve of the material: (a) Q345 steel; (b) high-strength bolts.

2.1.3. Element Type and Mesh Discretization

The beam-to-column joint is modeled using SOLID185 elements in ANSYS Mechanical APDL 2019 R1, as shown in Figure 3. Meshing is performed using a combination of mapped and swept techniques, with region-specific refinement. Critical regions are discretized with a mesh size of 12.5 mm × 11.5 mm × 10 mm, while bolt interfaces are refined with a mesh size of 4 mm × 4 mm × 4 mm. Similar mesh refinement strategies have been adopted in previous finite element studies [42]. The rest of the model is discretized using elements with dimensions of 12 mm × 12 mm × 36 mm.

2.1.4. Contact Settings and Boundary Conditions

Surface-to-surface contact is defined between the bolts, nuts, and plate-to-plate interfaces of the joint, with a friction coefficient of 0.44. A common time-step parameter is applied to all contact pairs. The contact behavior is modeled using TARGET170 and CONTACT174 elements. Bolt preloading is applied via thermal shrinkage, with equivalent temperature loads used to generate the required pretension.

The column base is fully constrained in all degrees of freedom, while the column top is free to rotate. At the rotation center, displacement is permitted only along the global X-axis. The analysis is conducted using ANSYS with the large-deformation option activated, using

the preconditioned conjugate gradient (PCG) solver and the Newton–Raphson iteration method. An automated two-step loading procedure is implemented: first, bolt preload is applied, followed by displacement-controlled loading at the beam end, as shown in Figure 4.

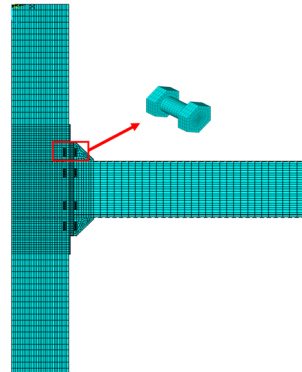


Figure 3. Finite element model of joints and bolts.

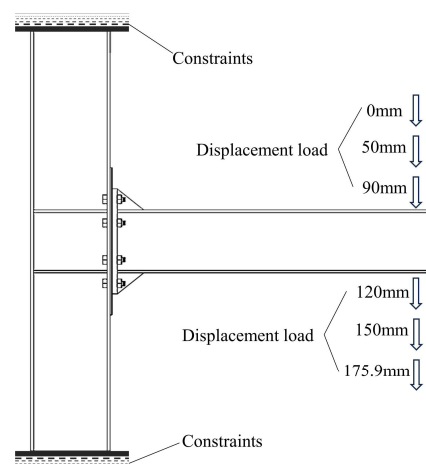


Figure 4. Loading scheme of the beam-to-column joint.

2.2. Analysis of Joint Rotation Characteristics

2.2.1. Deformation Patterns and Bending Moment–Rotation Curves

Figure 5 compares the finite element deformation contours with the experimentally observed damage patterns reported in the literature [41], showing close agreement in the deformation characteristics within the joint region. For specimen SC6, the dominant damage modes include significant plastic deformation of the beam end-plate and column flange, visible separation between the end-plate and column flange on the beam tension side, marked shear deformation of the column web within the joint region, and beam rotation about the axis defined by the compression flange–end-plate interface.

Figure 6 compares the bending moment–rotation curves obtained from numerical simulations with experimental results from the literature [41], showing overall good agreement. The joint’s rotation response can be divided into three distinct stages: elastic, yielding, and strengthening. In the elastic stage, the bending moment–rotation relationship is approximately linear, indicating a constant initial rotational stiffness. As the applied load increases, the joint enters the yielding stage, where the rotation increases nonlinearly with the bending moment, accompanied by a progressive reduction in rotational stiffness. With further loading, the strengthening stage begins, where the bending moment–rotation relationship becomes linear again and the rotational stiffness stabilizes until specimen failure.

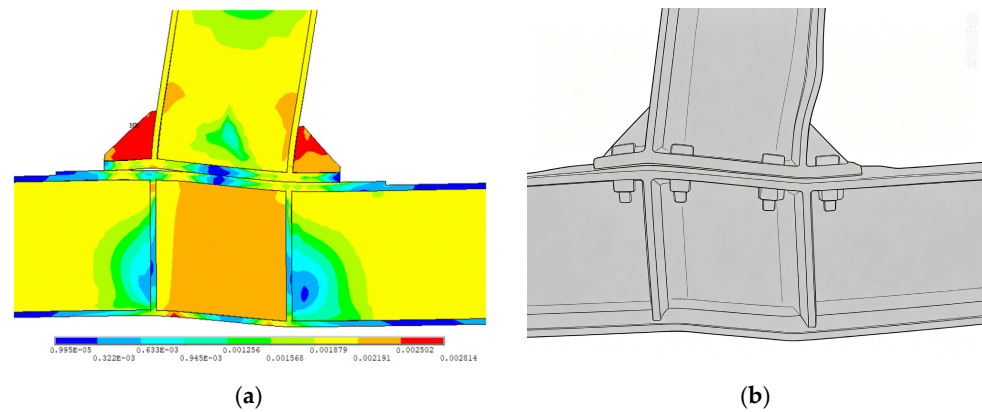


Figure 5. Comparison between numerical simulation and experimental deformation: (a) Deformation contours; (b) Experimental failure pattern (redrawn according to ref. [41]).

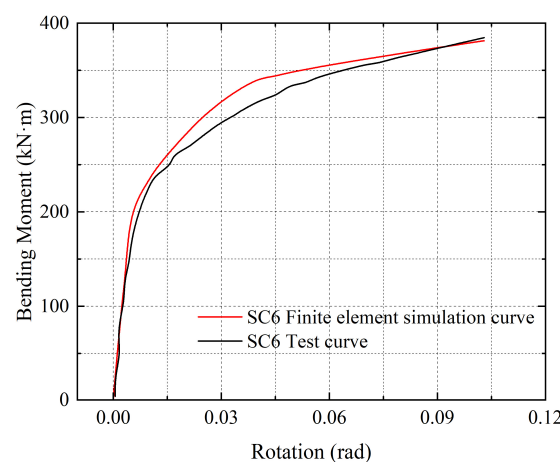


Figure 6. Bending moment–rotation curve.

For beam–column end-plate joints, finite element analysis accurately predicts the bending moment, rotation angle, and initial joint stiffness. The initial rotational stiffness obtained from finite element analysis is 46,540 kN·m/rad, the ultimate bending moment is 379 kN·m, and the ultimate rotation angle is 0.89 rad.

2.2.2. Stress Distribution Characteristics

Under bending moments, the joint experiences tension in the upper region and compression in the lower region. Figure 7 illustrates the stress distribution in the end-plate. Bolt preloading induces tensile forces in the bolts while generating uniformly distributed compressive stresses around the bolt holes at the nut–end-plate interfaces, as shown in Figure 7a. Figure 7b–f show the evolution of end-plate stress during loading, indicating that the stress magnitude increases proportionally with the beam-end displacement. Tensile stresses are mainly concentrated between the first and second bolt rows, while compressive stresses are primarily localized between the third and fourth bolt rows. Furthermore, examining the side-view stress contours of the end-plate, the failure process of the end-plate progresses from top to bottom. Initial yielding occurs near the first bolt row, followed by sequential yielding of the second and third bolt rows. Ultimately, at the ultimate limit state, significant deformation develops in the joint region, with end-plate rotation primarily concentrated between the third and fourth bolt rows, exhibiting a characteristic mirror-symmetric S-shaped deformation mode.

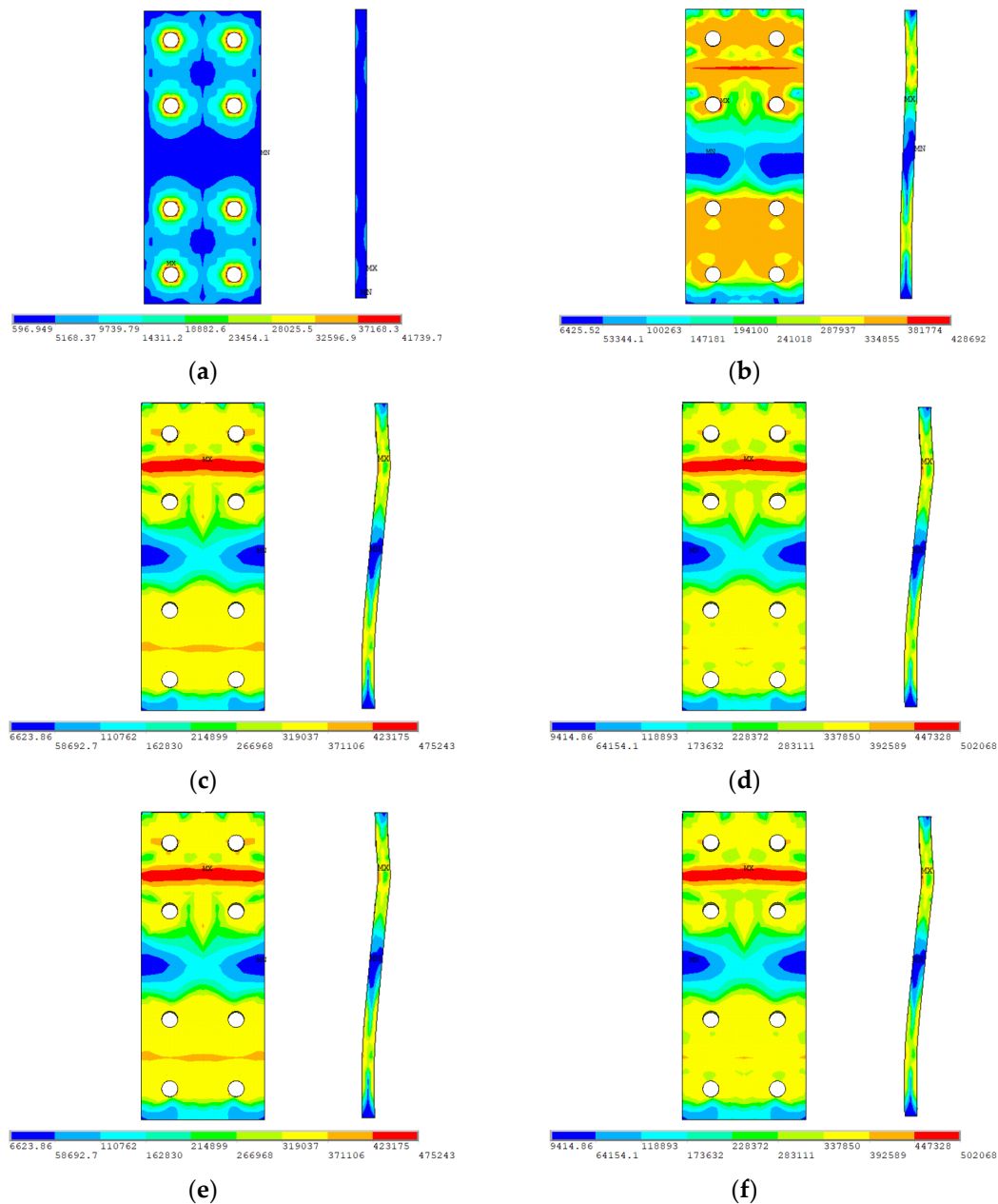


Figure 7. Stress distribution of end-plate under different load levels: (a) At a beam-end displacement of 0 mm; (b) At a beam-end displacement of 50 mm; (c) At a beam-end displacement of 90 mm; (d) At a beam-end displacement of 120 mm; (e) At a beam-end displacement of 150 mm; (f) At a beam-end displacement of 175.9 mm.

3. Joint Component Model

3.1. Model Description

In the proposed Joint Component Model (JCM), each bolt row in the beam-to-column joint is idealized as an independent component unit, as illustrated in Figure 8. Each unit consists of a spring–slider assembly connected in parallel with an elastic spring.

When the force in the spring–slider assembly reaches the prescribed yield force, yielding is activated, resulting in axial displacement of the component unit. The corresponding force–displacement relationship is expressed as

$$F = F(x) = \begin{cases} (K_i + K_{\infty,i})x & 0 < x \leq x_i^* \\ K_{\infty,i}x & x > x_i^* \end{cases}, \quad (1)$$

where K_i is the initial stiffness of the spring–slider assembly for the i -th bolt row, and $K_{\infty,i}$ is the residual stiffness provided by the parallel elastic spring. $K_i + K_{\infty,i}$ defines the total initial stiffness of the component unit, signifies axial displacement of the unit, and is the corresponding yield displacement.

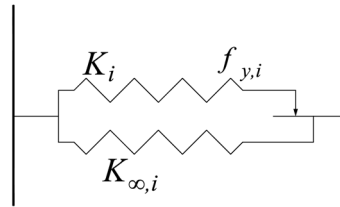


Figure 8. Component unit of the Joint Component Model.

A series of component units are connected in parallel to establish the proposed Joint Component Model (JCM), as illustrated in Figure 9. In this configuration, rods A and B are assumed to be rigid, and the component units are positioned between them to simulate the tensile behavior of the bolt rows.

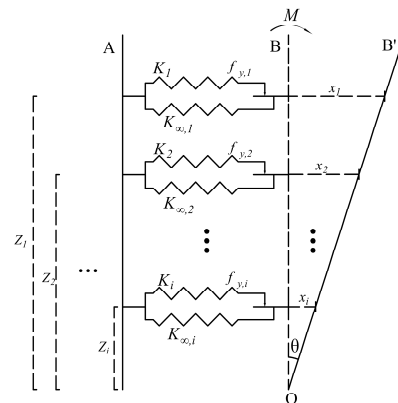


Figure 9. Schematic diagram of the Joint Component Model.

Rod A is fully constrained, while rod B is permitted to rotate about the rotation center O under the applied bending moment M , producing a rotation angle θ . The axial deformation of each component unit is therefore governed by the rotational displacement of rod B.

As the rotation increases, the component units yield sequentially from the upper bolt rows to the lower ones, leading to progressive stiffness degradation of the joint. Through this mechanism, the JCM provides a mechanical representation of the nonlinear rotational response of beam-to-column joints, as schematically illustrated in Figure 10.

3.2. Constitutive Relationship of the Model

In the JCM, the effective stiffness and tensile load-carrying capacity of each bolt row correspond directly to the initial stiffness and yield force of the associated component unit, respectively.

The bending moment acting on the joint is obtained by summing the contributions of the axial forces in all component units with respect to the rotation center:

$$M(\theta) = \begin{cases} \left[\sum_{i=1}^n (K_i + K_{\infty,i}) \right] z_i^2 \theta & 0 \leq \theta < \varphi_1 \\ \left(\sum_{i=j}^n K_i + \sum_{i=1}^n K_{\infty,i} \right) z_i^2 \theta + \sum_{i=1}^{j-1} f_{y,i} z_i & \varphi_{j-1} \leq \theta < \varphi_j, j \in [2, n], \\ \left(\sum_{i=1}^j K_{\infty,i} \right) z_i^2 \theta + \sum_{i=1}^j f_{y,i} z_i & \theta \geq \varphi_n \end{cases} \quad (2)$$

where i denotes the bolt-row index counted from top to bottom, z_i is the distance from i -th bolt row to the rotation center, $f_{y,i}$ denotes the yield force of the i -th component unit, j is a positive integer, and n is the total number of bolt rows located in the tension zone.

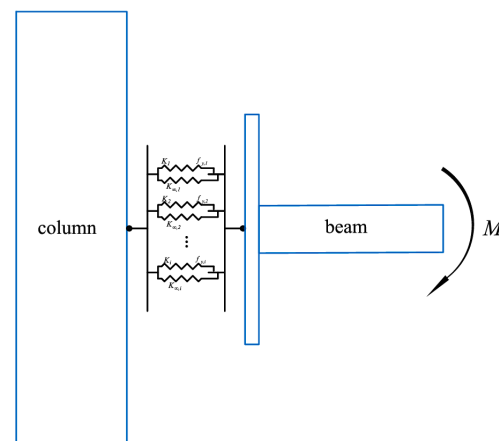


Figure 10. Beam-to-column joint schematic.

The rotation center is assumed to be located between the lowest tension bolt row and the compression zone, consistent with Eurocode-based component method assumptions for bolted end-plate connections. This represents a commonly adopted idealization for typical symmetric and semi-symmetric joint configurations within the scope of the proposed modeling framework.

Based on the above formulation, the moment-rotation relationship of the joint is derived. The resulting skeleton curve of the JCM, shown in Figure 11, consists of three distinct stages: the elastic stage, yielding stage and strengthening stage.

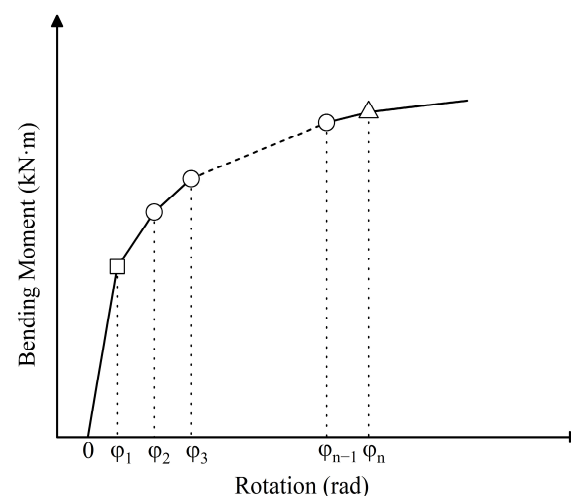


Figure 11. Theoretical bending moment-rotation curve of the SC6 joint.

In Figure 11, the symbol $\square$ denotes the initiation of the yielding stage, while $\triangle$ indicates the onset of the strengthening stage. The curve segment between $\square$ and $\triangle$ is divided into $n - 1$ subsegments, corresponding to the sequential yielding of $n - 1$ component units. For rotation angles satisfying $0 \leq \theta < \varphi_1$, the bending moment–rotation relationship remains linear. With increasing bending moment, the tensile forces in the component units increase without yielding, and the model behaves equivalently to a linear rotational spring. When $\theta \geq \varphi_n$, the joint enters the strengthening stage, exhibiting a linear bending moment–rotation relationship in which all component units have fully yielded, and the residual rotational stiffness stabilizes at $\left(\sum_{i=1}^j K_{\infty,i}\right) z_i^2$.

Furthermore, the rotational stiffness of the JCM is obtained by differentiating Equation (2) with respect to the rotation angle θ :

$$K(\theta) = \begin{cases} \left[\sum_{i=1}^n (K_i + K_{\infty,i}) \right] z_i^2 & 0 \leq \theta < \varphi_1 \\ \left(\sum_{i=j}^n K_i + \sum_{i=1}^n K_{\infty,i} \right) z_i^2 & \varphi_{j-1} \leq \theta < \varphi_j, j \in [2, n] \\ \left(\sum_{i=1}^j K_{\infty,i} \right) z_i^2 & \theta \geq \varphi_n \end{cases} \quad (3)$$

Equation (3) shows that the rotational stiffness of the Joint Component Model remains constant during the initial elastic stage. As the joint enters the yielding stage, the stiffness decreases progressively due to the sequential yielding of component units. After the transition to the strengthening stage, the stiffness stabilizes at a constant residual value governed by the post-yield behavior of the components.

3.3. Parameter Identification

The JCM incorporates four primary parameters: the initial stiffness of the component unit $(K_i + K_{\infty,i})$, the residual stiffness $K_{\infty,i}$, the yield force $f_{y,i}$ and the yield rotation φ_j . Except for the residual stiffness $K_{\infty,i}$, which depends on the reinforced stiffness coefficients of individual components, the remaining parameters are determined directly from joint geometric characteristics.

3.3.1. Identification of Stiffness Parameters of Component Units

The Joint consists of four component types: column web in tension, column flanges in bending, end-plate in bending, and bolts in tension. Assuming parallel spring behavior, the initial stiffness of the i -th component unit denoted by $(K_i + K_{\infty,i})$, while $(k_i + k_{\infty,i})$ represents the effective initial stiffness coefficient of the i -th component unit. The stiffness coefficient $(k_i + k_{\infty,i})$ can be calculated using the following expression:

$$(K_i + K_{\infty,i}) = E(k_i + k_{\infty,i}), \quad (4)$$

$$\sum \frac{1}{(k_i + k_{\infty,i})} = \frac{1}{k_{i,wc}} + \frac{1}{k_{i,cf}} + \frac{1}{k_{i,ep}} + \frac{1}{k_{i,bt}}, \quad (5)$$

where E denotes the elastic modulus of steel, k_{wc} represents the stiffness coefficient of the column web in tension, k_{cf} represents the stiffness coefficient of the column flange in bending, k_{ep} corresponds to the stiffness coefficient of the end-plate in bending, and k_{bt} defines stiffness coefficient of the tensile bolt.

The column web in tension and the column flange in bending are idealized as equivalent beam-to-column components, as illustrated in Figure 12. It should be noted that the T-stub model considered in this study is not intended to represent the entire connection.

Instead, it serves as an equivalent mechanical component within the component-based representation of a bolted extended end-plate connection.

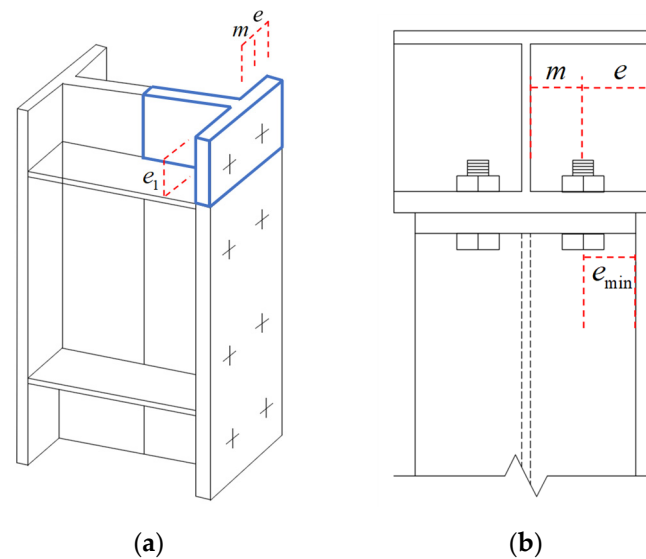


Figure 12. Equivalent T-stub model for the column flange in bending and the column web in tension: (a) Axonometric view; (b) Top view.

Based on this idealization, the stiffness coefficient of the column web in tension can be expressed as follows:

$$k_{wc} = \frac{0.7b_{eff,t,wc}t_{wc}}{d_c}, \quad (6)$$

$$b_{eff,t,wc} = \min\{2\pi m, \pi m + 2e_1\}, \quad (7)$$

where $b_{eff,t,wc}$ represents the effective width of the column web in tensile (equivalent to the effective length of the T-stub component), t_{wc} denotes the thickness of the column web, and d_c is the net height of the column web.

The stiffness coefficient of the column flange in bending is given by

$$k_{cf} = \frac{0.9l_{eff,b,cf}t_{fc}^3}{m^3}, \quad (8)$$

where $l_{eff,b,cf} = \min\{2\pi m, \pi m + 2e_1\}$ denotes the effective length of the column flange in bending corresponding to the considered bolt row, and t_{fc} represents the thickness of the column flange.

The end-plate is idealized as equivalent T-stub components, as illustrated in Figure 13. The stiffness coefficient can therefore be expressed as

$$k_{ep} = \frac{0.9l_{eff,b,ep}t_p^3}{m^3}, \quad (9)$$

where $l_{eff,b,ep} = \min\{2\pi m_x, \pi m_x + w, \pi m_x + 2e\}$ denotes the effective length of the end-plate corresponding to the considered bolt row, and t_p represents the thickness of the end-plate.

The dimensions of the high-strength bolts are illustrated in Figure 14. The corresponding stiffness coefficient of the bolt can be expressed as

$$k_{bt} = \frac{1.6A_s}{L_b}, \quad (10)$$

where A_s denotes the tensile cross-sectional area of the preloaded bolt, and L_b represents the bolt elongation length, defined as half the sum of the bolt shank length, washer thickness, bolt head height, and nut height.

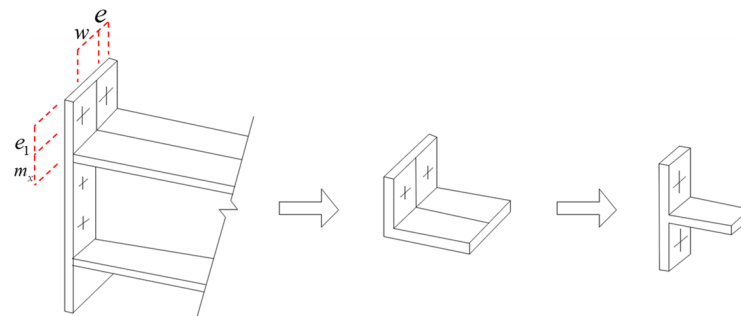


Figure 13. The T-stub steel component of the end-plate.

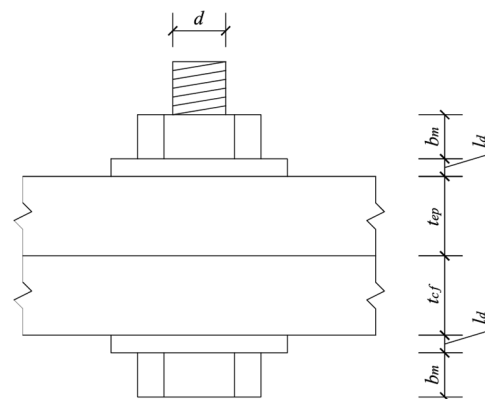


Figure 14. Basic dimensions of the bolts.

3.3.2. Identification of Residual Stiffness Parameters of Component Units

The residual stiffness of component units is determined by the strain-hardening stiffness coefficients of the individual components. Following the strain-hardening stiffness formulation proposed in Ref. [43], the residual stiffness of each component is assumed to be proportional to the tangent modulus of steel in the strain-hardening stage. In the present study, a tangent modulus equal to 1.5% of the elastic modulus is adopted as an engineering approximation for implementing the proposed Joint Component Model. Accordingly, the residual stiffness $K_{\infty,i}$ of each component unit and the corresponding residual stiffness coefficient $k_{\infty,i}$ can be expressed as follows:

$$K_{\infty,i} = E \cdot k_{\infty,i}, \quad (11)$$

$$k_{\infty,i} = \frac{E_{st}}{E} k_i, \quad (12)$$

where E_{st} is the tangent modulus of steel in the strain-hardening stage, E is the elastic modulus of steel, and k_i is the initial stiffness coefficient associated with K_i for the spring–slider assembly of the i -th bolt row.

It should be noted that k_i denotes the equivalent stiffness coefficient of the entire component rather than a material property of steel alone. Therefore, the residual stiffness is obtained by scaling the component stiffness according to the strain-hardening tangent modulus, while the effects of connection geometry and bolt deformation remain implicitly incorporated in the component stiffness.

3.3.3. Identification of Yield Strength Parameters of Component Units

The yield force of each component unit is determined by the design tensile capacities of four fundamental components: the column web in tensile ($F_{t,wc}$), the column flange in bending ($F_{t,cf}$), the end-plate in bending ($F_{t,ep}$), and the tensile beam web ($F_{t,wb}$). The governing yield force of the component unit $f_{y,i}$ is taken as the minimum value among these four capacities:

$$f_{y,i} = \min\{F_{t,wc}, F_{t,cf}, F_{t,ep}, F_{t,wb}\} \quad (13)$$

(1) Design resistance of the column web in tension

$$F_{t,wc} = \frac{\omega b_{eff,t,wc} t_{wc} f_{y,wc}}{\gamma_{M0}} \quad (14)$$

$$\omega = \omega_1 = \frac{1}{\sqrt{1 + 1.3(b_{eff,t,wc} / A_{vc})}} = 1, \quad (15)$$

where $b_{eff,t,wc}$ denotes the effective width of the column web in tension (equivalent to the effective length of the T-beam flange), t_{wc} represents the column web thickness, γ_{M0} is the joint partial safety factor, A_{vc} denotes the shear area of the column web, and $f_{y,wc}$ is the steel yield strength.

(2) Design resistance of the column flange in bending

The design resistance of the column flange in bending is obtained from the corresponding T-stub model, taking the minimum value among three failure modes: (i) yielding of the T-stub flange, (ii) bolt failure, and (iii) combined yielding of the flange with bolt failure. Accordingly, the design resistance of the column flange is calculated using the following expression:

$$F_{t,cf} = \min\{F_{T,1}, F_{T,2}, F_{T,3}\}, \quad (16)$$

where $F_{T,1}$, $F_{T,2}$ and $F_{T,3}$ denote the bearing capacities associated with the three failure modes, namely flange yielding, bolt failure, and combined flange yielding with bolt failure, respectively.

The details are as follows:

$$F_{T,1} = \frac{4M_{pl,1,wc}}{m} \quad (17)$$

$$M_{pl,1,wc} = 0.25l_{eff,b,cf} t_f^2 f_{y,cf} / \gamma_{M0}, \quad (18)$$

where $l_{eff,b,cf}$ denotes the effective length of the T-beam flange, t_f represents the column flange thickness, γ_{M0} is the joint partial safety factor, and $f_{y,cf}$ is the steel yield strength.

$$F_{T,2} = \frac{2M_{pl,2,wc} + e_{\min} \sum F_{t,wc}}{m + e_{\min}} \quad (19)$$

$$M_{pl,2,wc} = 0.25l_{eff,b,cf} t_f^2 f_{y,cf} / \gamma_{M0} \quad (20)$$

$$F_{t,wc} = \frac{k_2 f_{u,b} A_s}{\gamma_{M2}}, \quad (21)$$

where $l_{eff,b,cf}$ denotes the effective length of the T-beam flange, t_f represents the column flange thickness, $f_{y,cf}$ is the steel yield strength, k_2 is a material constant, $f_{u,b}$ is the ultimate tensile strength of the bolt, γ_{M0} and γ_{M2} are partial safety factors for joint components, and A_s is the tensile cross-sectional area of the bolt.

$$F_{T,3} = \sum F_{t,wc} \quad (22)$$

(3) Design resistance of the end-plate in bending

The design resistance of the end-plate in bending is obtained from the corresponding T-stub model, taking the minimum value among three failure modes: (i) flange yielding, (ii) bolt failure, and (iii) combined flange yielding and bolt failure.

$$F_{t,ep} = \min\{F_{T,a}, F_{T,b}, F_{T,c}\} \quad (23)$$

$$F_{T,a} = \frac{4M_{pl,1,ep}}{m} \quad (24)$$

$$M_{pl,1,ep} = 0.25l_{eff,b,ep}t_f^2f_{y,ep}/\gamma_{M0} \quad (25)$$

where $m = m_x$, $l_{eff,b,ep}$ denotes the effective length of the T-beam flange, t_f represents the end-plate thickness, γ_{M0} is the joint partial safety factor, and $f_{y,ep}$ is the yield strength of the end-plate steel.

$$F_{T,b} = \frac{2M_{pl,2,ep} + e_{\min}\sum F_{t,ep}}{m + e_{\min}} \quad (26)$$

$$M_{pl,2,ep} = 0.25l_{eff,b,ep}t_f^2f_{y,ep}/\gamma_{M0} \quad (27)$$

$$F_{t,ep} = \frac{k_2f_{u,b}A_s}{\gamma_{M2}}, \quad (28)$$

where $l_{eff,b,cf}$ denotes the effective length of the T-beam flange, t_f represents the column flange thickness, $f_{y,ep}$ is the steel yield strength, k_2 is a constant, $f_{u,b}$ is the ultimate tensile strength of the bolt, γ_{M0} and γ_{M2} indicate partial safety factors for joint resistance, and A_s is the tensile cross-sectional area of the bolt.

$$F_{T,3} = \sum F_{t,wc} \quad (29)$$

(4) Design resistance of the beam web in tension

The design resistance of the beam web in tension is determined as

$$F_{t,wb} = b_{eff,t,wb}t_{wb}f_{y,wb}/\gamma_{M0} \quad (30)$$

where $b_{eff,t,wb}$ denotes the effective width of the beam web in tensile, which is equivalent to the effective length of the end-plate $l_{eff,b,ep}$ associated with the T-stub flange; t_{wb} represents the beam web thickness; $f_{y,wb}$ is the steel yield strength; and γ_{M0} is the joint partial safety factor.

3.3.4. Identification of Characteristic Rotation Angles

The rotation angle φ_1 at the initiation of the yielding stage, the sequence of rotation angles $\varphi_1 \sim \varphi_n$ corresponding to the progressive yielding of component units, and the rotation angle φ_n at the onset of the strengthening stage are determined as follows:

$$\varphi_j = \frac{f_{y,i}}{K_i} \cdot \frac{1}{z_i} \quad (31)$$

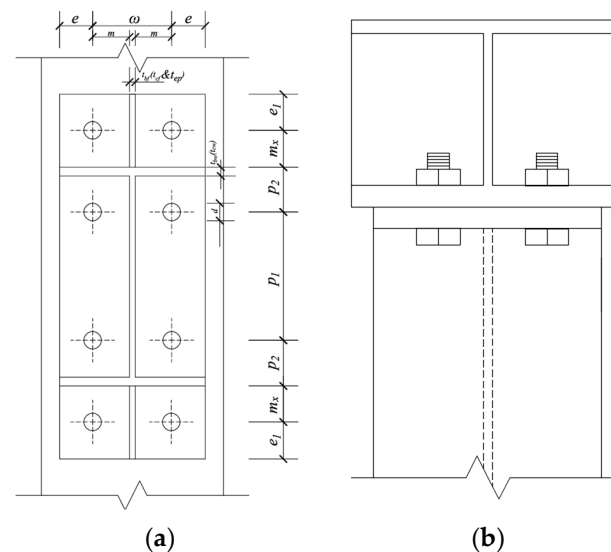
4. Application of Component Models

4.1. Constitutive Relations and Parameters

The proposed component model is applied to the SC6 joint. The geometric parameters of the SC6 specimen are summarized in Table 1. Detailed views of the end-plate and the beam-to-column joint configuration are presented in Figure 15.

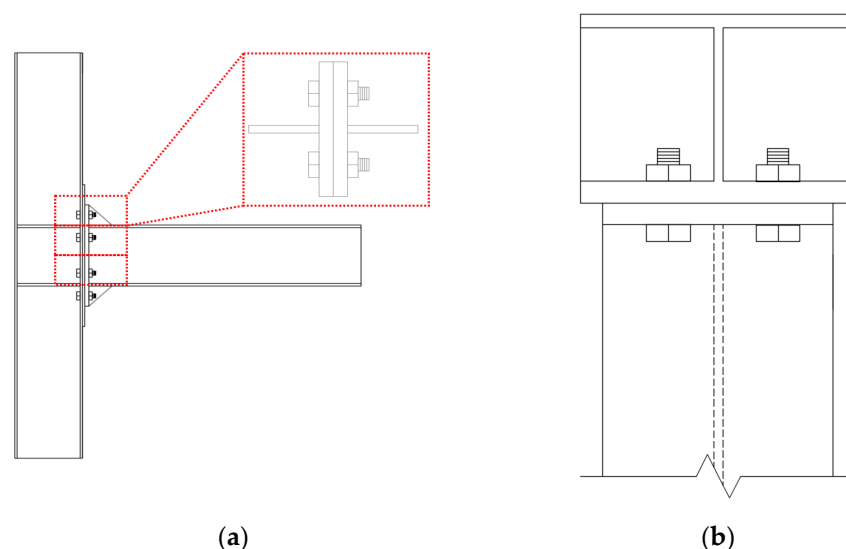
Table 1. The specific size of the joint (mm).

Test Piece	e	e_1	m	m_x	ω	p_1	p_2	d	t_{bw}	t_{bf}
SC6	46	50	50	50	108	176	62	24	12	8

**Figure 15.** Details of the SC6 joint: (a) End-plate detail; (b) Plan view of the joint.

The SC6 joint contains three rows of bolts in the tension zone, with the rotation center located between the third and fourth bolt rows. Based on the modelling procedure described in Section 3.2, the corresponding Joint Component Model (JCM) is established, as illustrated in Figure 16. The resulting nonlinear moment–rotation relationship of the joint is expressed by Equation (32):

$$M(\theta) = \begin{cases} (K_1 z_1^2 + K_2 z_2^2 + K_3 z_3^2 + K_{\infty,1} z_1^2 + K_{\infty,2} z_2^2 + K_{\infty,3} z_3^2) \theta & 0 \leq \theta < \varphi_1 \\ (K_2 z_2^2 + K_3 z_3^2 + K_{\infty,1} z_1^2 + K_{\infty,2} z_2^2 + K_{\infty,3} z_3^2) \theta + f_{y,1} z_1 & \varphi_1 \leq \theta < \varphi_2 \\ (K_3 z_3^2 + K_{\infty,1} z_1^2 + K_{\infty,2} z_2^2 + K_{\infty,3} z_3^2) \theta + f_{y,1} z_1 + f_{y,2} z_2 & \varphi_2 \leq \theta < \varphi_3 \\ (K_{\infty,1} z_1^2 + K_{\infty,2} z_2^2 + K_{\infty,3} z_3^2) \theta + f_{y,1} z_1 + f_{y,2} z_2 + f_{y,3} z_3 & \theta \geq \varphi_3 \end{cases} \quad (32)$$

**Figure 16.** Joint Component Model of the SC6 joint: (a) SC6 joint configuration; (b) Joint Component Model (JCM).

The parameters of the SC6 Joint Component Model (JCM) were determined using the identification procedure described in Section 3.3. The resulting parameter values are summarized in Table 2.

Table 2. Parameter identification results.

Parameters		K_n (kN/m)	$f_{y,n}$ (kN)	$K_{\infty,n}$ (kN/m)	z_i (m)
Row					
	$n = 1$	415,000	353	6225	0.35
	$n = 2$	443,000	465	6645	0.238
	$n = 3$	443,000	465	6645	0.062

A finite element model of specimen SC6 was established in ANSYS, as shown in Figure 17. Linear elastic material behavior was assumed for all structural components, with an elastic modulus of 200 GPa and a Poisson's ratio of 0.3. The beams, columns, end-plates, and stiffeners were modeled using SOLID185 elements. Both ends of the column were fully restrained, whereas the right end of the beam was left free. The proposed JCM was introduced between the beam end-plate and the column flange to represent the nonlinear rotational response of the connection.

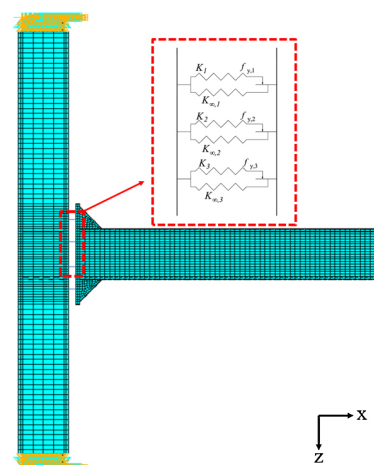


Figure 17. Finite element implementation of the Joint Component Model for the SC6 joint.

In ANSYS, each component unit of the Joint Component Model (JCM) is represented by a parallel combination of COMBIN40 and COMBIN14 elements. The COMBIN40 element is used to simulate the elastic–plastic behavior of the component unit, with the spring stiffness and yield force specified through real constants. Only the spring and slider functions are activated (KEYOPT(3) = 1), and the active degree of freedom is defined as UX.

The COMBIN14 element is employed to model the residual stiffness of the component unit. It is configured as a one-dimensional tension spring without damping (KEYOPT(2) = 1), with UX assigned as the active degree of freedom.

The boundary conditions and loading scheme are consistent with those used in the direct numerical simulation of the beam-to-column joint presented in Section 2. The moment–rotation curve predicted by the JCM is shown in Figure 18. As can be seen, the JCM reproduces the overall moment–rotation response with good accuracy. A slight overestimation of the initial rotational stiffness is observed compared with the direct numerical simulation results. The coefficient of determination R^2 and root mean square error RMSE between the DNS and JCM results were approximately 0.93 and 30.9, respectively, indicating good agreement between the two models over the entire response range.

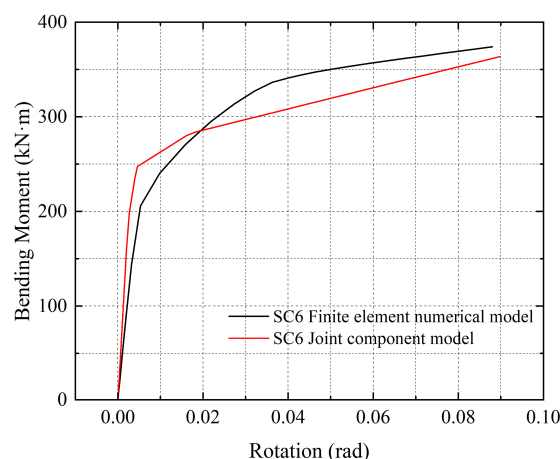


Figure 18. Comparison of moment–rotation curves obtained from the Joint Component Model and direct numerical simulation.

4.2. Application of the Joint Component Model to Steel Frames

To further validate the proposed Joint Component Model (JCM), it is applied to the analysis of steel frames. Direct numerical simulation (DNS) is conducted for the same structural configuration, and the results obtained from the two modelling approaches are compared.

4.2.1. Finite Element Model of the Steel Frame

The steel frame considered in this study is shown in Figure 19. A representative single-bay, single-story steel frame is adopted to demonstrate the structural-level application of the proposed Joint Component Model (JCM), similar to representative frame configurations adopted in previous studies [44]. It consists of two beam-to-column joints with the same configuration as specimen SC6. The frame span and story height are 6 m and 3 m, respectively. The joint geometry is identical to that of specimen SC6 reported in Ref. [41], while the beam and column cross-sectional dimensions are those described in Section 2.1.1.

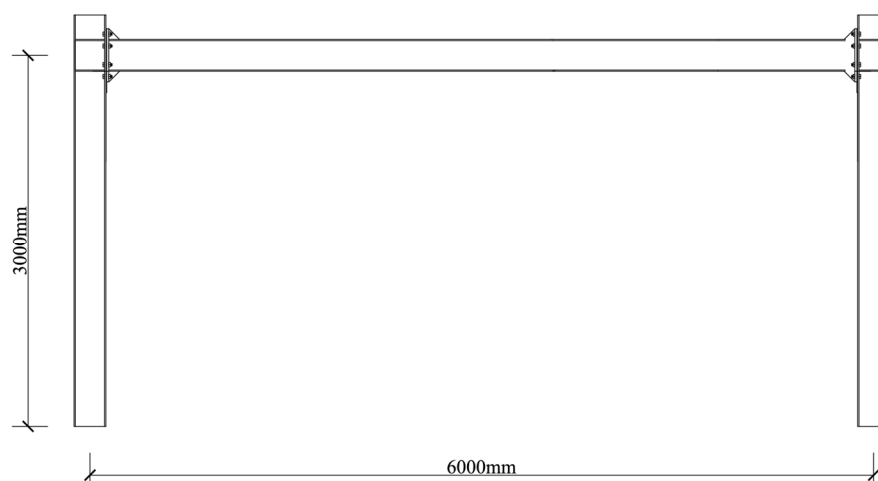


Figure 19. Geometry of the single-story steel frame.

All frame members are fabricated from Q345 structural steel, whose constitutive relationship is shown in Figure 2. The beams and columns are modeled using solid elements and discretized according to the meshing strategy described in Section 2.1.3.

In the direct numerical simulation (DNS), the beam-to-column joints and bolts are explicitly represented using solid elements. The contact formulations, friction coefficients, and bolt preload procedures are identical to those adopted in the joint-level DNS presented in Section 2. The corresponding finite element model is shown in Figure 20.

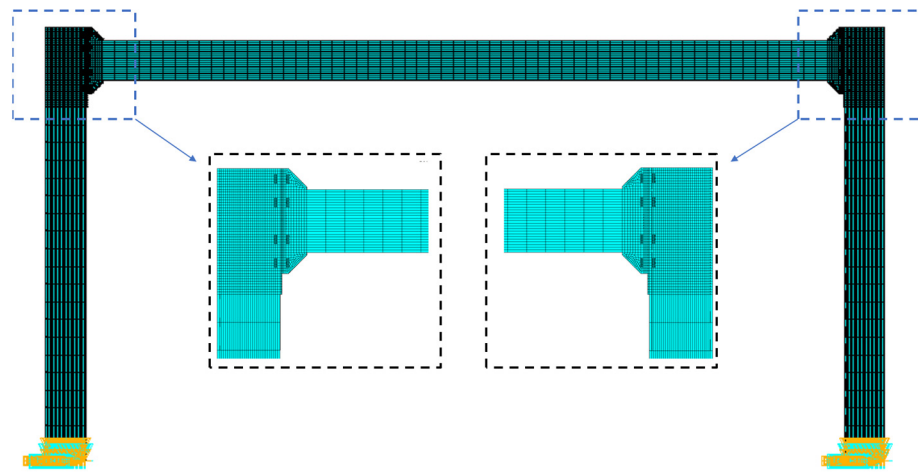


Figure 20. Direct numerical simulation model of the steel frame.

When the Joint Component Model (JCM) is adopted, the beam-to-column joints are represented by the simplified joint model described in Section 4.2. The resulting finite element model is shown in Figure 21.

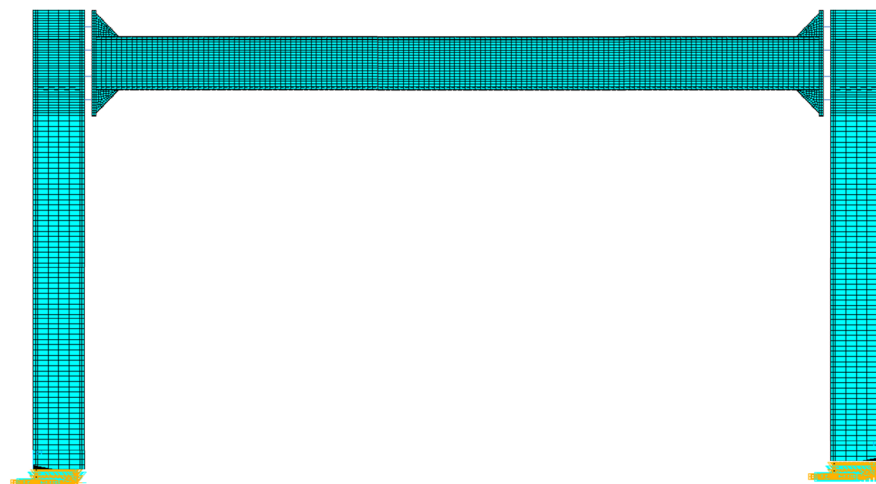


Figure 21. Finite element model of the steel frame based on the Joint Component Model (JCM).

4.2.2. Boundary Conditions

For both the direct numerical simulation (DNS) and the Joint Component Model (JCM), the same boundary conditions are adopted. The column base is fully restrained in all degrees of freedom, while the top of the column is left free. Both static and dynamic loading conditions are considered. The static loading cases include vertical and horizontal loading, as illustrated in Figure 22. Geometric nonlinearity is taken into account throughout the analysis.

The analysis is performed in two consecutive steps. First, a bolt preload of 225 kN is applied, which is considered only in the direct numerical simulation (DNS). Subsequently, displacement-controlled loading is imposed.

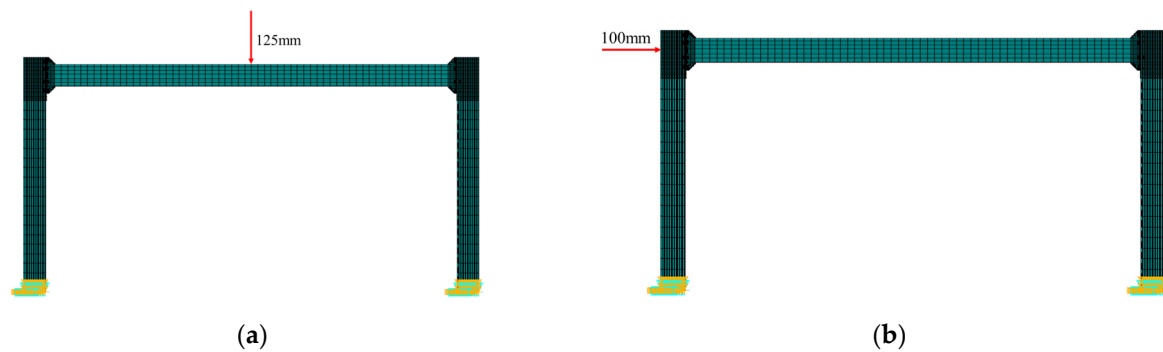


Figure 22. Static loading configurations for the steel frame: (a) Vertical loading; (b) Horizontal loading.

For the dynamic analysis, a lateral excitation is applied in the global x-direction of the frame. A natural earthquake record (El Centro wave) was selected to represent the seismic input under a fortification intensity of 7 degrees. The full integration method was adopted for the transient dynamic analysis. According to the requirements of the Code for Seismic Design of Buildings [45] regarding the peak value of acceleration time histories used in time-history analysis, the earthquake record was amplitude-scaled such that its peak ground acceleration was adjusted to 35 cm/s^2 . The corresponding acceleration time history is shown in Figure 23.

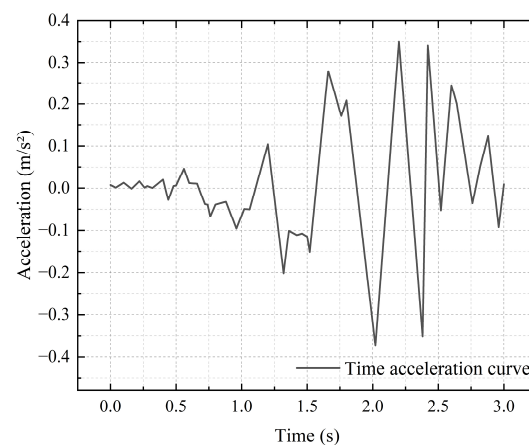


Figure 23. Acceleration time-history record.

4.2.3. Results Analysis

(1) Vertical and horizontal loading cases

Figure 24 compares the force–displacement responses of the steel frame obtained from the Joint Component Model (JCM) and the direct numerical simulation (DNS). The results under vertical and horizontal loading are shown in Figure 24a,b, respectively. As can be seen, the two approaches produce highly consistent responses, indicating that the proposed JCM accurately captures the global behavior of the steel frame under static loading.

At low load levels, the steel frame exhibits a nearly linear elastic response. As the applied load increases, the component units within the beam-to-column joints yield sequentially, leading to stiffness degradation and pronounced nonlinearity in the force–displacement response. Once all component units have yielded, the structural response gradually enters the strengthening stage. Owing to the residual stiffness incorporated in the Joint Component Model (JCM), the force–displacement relationship regains an approximately linear trend at higher load levels.

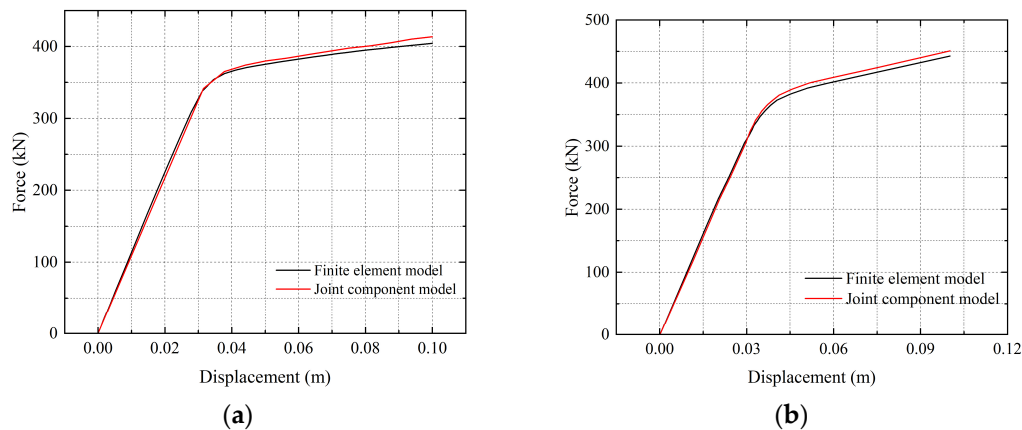


Figure 24. Comparison of force–displacement responses obtained from the Joint Component Model and direct numerical simulation: (a) Vertical loading; (b) Horizontal loading.

(2) Dynamic loading

Figure 25 presents the displacement time-history responses at the midspan of the steel frame predicted by the Joint Component Model (JCM) and the direct numerical simulation (DNS). Excellent agreement is observed between the two sets of results in terms of both amplitude and overall response trend. These results indicate that the proposed JCM can accurately capture the dynamic characteristics of the steel frame while significantly reducing computational complexity.

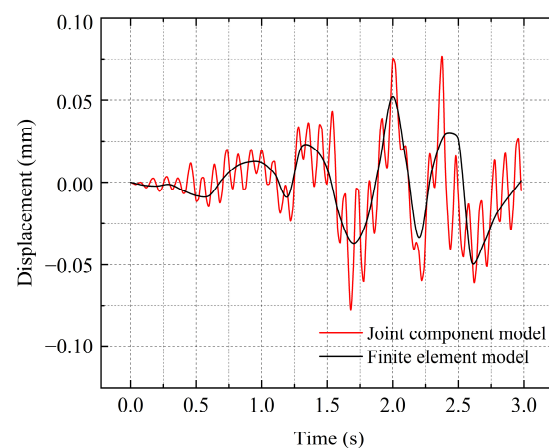


Figure 25. Displacement time-history curve at midspan of the steel frame.

The comparisons presented in Figures 24 and 25 confirms that the proposed Joint Component Model (JCM) can accurately reproduce both the static and dynamic responses of the steel frame. To further evaluate the computational efficiency of the proposed approach, a quantitative comparison between the direct numerical simulation (DNS) model and the JCM is summarized in Table 3.

Table 3. Comparison of computational efficiency between DNS and JCM.

Beam-to-Column Joint Model	Joint Element Type	Beam/Column Element Type	Contact DOFs	Static Analysis Time (Steel Frame)	Dynamic Analysis Time (Steel Frame)
DNS	Solid	Solid	57,384	1 h	4 h
JCM	Spring–slider	Solid	2	30 s	120 s

As shown in Table 3, the DNS model requires 57,384 contact degrees of freedom to represent the beam-to-column joint behavior, whereas the proposed JCM reduces this number to only 2 through the use of spring and spring–slider elements. This substantial reduction in model complexity leads to a significant improvement in computational efficiency. For the static analysis of the single-story steel frame, the computational time decreases from approximately 1 h for the DNS model to about 30 s for the JCM. For the dynamic analysis, the required computational time is reduced from approximately 4 h to 120 s.

These results demonstrate that the proposed JCM achieves an effective balance between prediction accuracy and computational efficiency, making it particularly suitable for large-scale structural analyses and dynamic simulations of steel structures.

5. Conclusions

Direct numerical simulations of beam-to-column joints were carried out to investigate their failure mechanisms and nonlinear rotational behavior. The numerical predictions showed good agreement with available experimental results, validating the adopted modeling approach. Based on the observed joint behavior, a Joint Component Model (JCM) was proposed to characterize the nonlinear moment–rotation response of bolted end-plate connections. The model parameters can be directly identified from joint geometric properties and possess clear physical interpretations. By incorporating residual rotational stiffness, the proposed JCM provides a more accurate representation of post-yield joint behavior than conventional component methods, while retaining a simple and efficient modeling framework. Although only a representative extended end-plate connection was investigated in this study, the proposed modeling framework is formulated in terms of component stiffness and resistance and can be extended to other connection configurations by modifying the corresponding component parameters.

In the proposed Joint Component Model (JCM), the stiffness and yield force of each component unit correspond directly to the effective stiffness and tensile resistance of the associated bolt row. The constitutive relationship is governed by the number of bolt rows located in the tension zone. The resulting moment–rotation skeleton curve exhibits three distinct stages: elastic, yielding, and strengthening. During the yielding stage, the component units yield sequentially from the upper to the lower bolt rows, resulting in progressive stiffness degradation. Once all component units have yielded, the joint enters the strengthening stage, where the moment–rotation response regains an approximately linear trend due to the residual rotational stiffness incorporated in the model.

An efficient implementation strategy of the proposed Joint Component Model (JCM) was developed in ANSYS using spring and spring–slider elements. The model was subsequently applied to the static and dynamic analyses of a steel frame and validated against direct numerical simulation (DNS) results. Excellent agreement was achieved in terms of both static and dynamic structural responses. Meanwhile, the proposed JCM significantly reduced the computational cost, decreasing the analysis time from approximately 1 h to 30 s for static analysis and from 4 h to approximately 120 s for dynamic analysis. These results demonstrate that the proposed JCM provides an effective balance between accuracy and computational efficiency and is well suited for large-scale structural analyses and dynamic simulations of steel structures.

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Abbreviations

The following abbreviations are used in this manuscript:

JCM Joint component model
DNS Direct numerical simulation

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