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Analysis on Structural Behavior of Semi-Rigid Joint in Steel Frame

Zhuofan Wu *

Department of Mechanical, Aerospace and Civil Engineering, University of Manchester, Manchester, UK

* Corresponding Author Email: 1813010110@stu.hrbust.edu.cn

Abstract. In the field of modern construction, steel structures have become the primary material of choice for design and construction. As a novel type of steel structure connection, the semi-rigid connection displays enhanced anti-collapse capabilities and energy dissipation characteristics under dynamic loading, offering significant research value and promising application prospects. Semi-rigid connections possess a combination of stiffness, ductility and load capacity, and are relatively straightforward to construct. These are practical and economically viable connection methodologies. This paper presents a summary of the specifications and classifications of semi-rigid joints as outlined in domestic and international literature. It also provides an overview of the characteristics and types of semi-rigid joints used in steel structures, along with an examination of the research methods and findings related to these joints. The paper aims to offer insights and guidance for the advancement of knowledge in the field of semi-rigid joints in steel structures, including their research, design, and practical applications.

Keywords: Structural behavior; Semi-rigid Joint; Steel frame.

1. Introduction

The use of steel structures in modern construction is becoming increasingly prevalent, particularly in the context of bridges, assembled buildings, high-rise structures and steel-concrete composites. The distinctive attributes of steel structures render them the preferred option for design and construction. As a consequence of scientific and technological progress and the enhancement of aesthetic expectations, the diversity and aesthetic appeal of steel structures have become a significant trend in the evolution of modern spatial structures. Steel has become a prevalent material in China's construction industry due to its lightweight nature, high strength, malleability, and durability, which collectively enhance the efficiency of engineering construction.

As China's comprehensive national strength and economic construction continue to develop, the improvement of assembled steel structure buildings in terms of building scale and construction management level provides a favourable opportunity for further growth. In the early years of the 21st century, there was a notable shift in the proportion of structures utilising steel and reinforced concrete. Steel structure buildings are increasingly prevalent in the domain of ultra-high-rise, heavy load, and movable structures, and are more frequently employed in the design of small and medium-span structures [1]. Therefore, it is crucial to conduct a comprehensive analysis of the design and calculation methods employed in the construction of steel structures, with a particular focus on the latest and most effective connection forms.

This study presents a synthesis of the research findings on semi-rigid connections published in recent years, employing a systematic review of the literature. The analysis primarily concentrates on the design codes, classification criteria and damage behaviour under loading of semi-rigid connections in steel buildings.

2. Design Criteria for Semi-rigid Connections

Relevant studies show that rigid connections invariably exhibit a degree of flexibility, while articulated connections similarly demonstrate a degree of rigidity [2, 3]. It is therefore evident that the ideal rigid and articulated connections do not exist. In practical engineering, the connection form of the beam-column node is predominantly semi-rigid. A semi-rigid connection represents a hybrid form of connection, combining the characteristics of both rigid and articulated connections. This connection is distinguished by its capacity to undergo some degree of relative rotation when external loads are applied, though the extent of this rotation is less fixed than that observed in a fully rigid connection. This type of connection is distinguished by a certain degree of stiffness, which provides partial restraint when the structure is subjected to forces that affect its overall performance. Furthermore, semi-rigid connections have the additional benefit of extending the structural period, increasing damping, and reducing amplitude. They also effectively absorb the energy generated under seismic action [4, 5].

2.1. European Standard

The semi-rigid connection is defined in the European steel construction code, EUROCODE 3, as a connection type situated between fully rigid and hinged connections [6]. Its behavioural characteristics include a certain rotational stiffness and moment carrying capacity. The Eurocodes provide clear definitions of rigid, semi-rigid and flexible connections based on the joint stiffness.

As illustrated in Fig. 1, $S_{j,ini}$ represents the initial slope of the joint moment - angle ($M-\theta_R$) curve. The classification of joints into rigid, semi-rigid, and nominally hinged categories is based on the value of rotational stiffness, denoted by the symbol $S_{j,ini}$. The division intervals of the various joint categories are presented in equations (1) to (3), respectively. In which the following variables are defined: The rotational stiffness ($S_{j,ini}$), moment of inertia of the beam section (I_b), beam span (L_b), modulus of elasticity (E), and stiffness coefficient (k_b) are the key parameters that determine the classification of a joint. The value of k_b is 8 for supported beams, and 25 for unsupported beams.

$$S_{j,ini} \geq k_b EI_b/L_b \tag{1}$$

$$0.5EI_b/L_b \leq S_{j,ini} \leq k_b EI_b/L_b \tag{2}$$

$$S_{j,ini} \leq 0.5EI_b/L_b \tag{3}$$

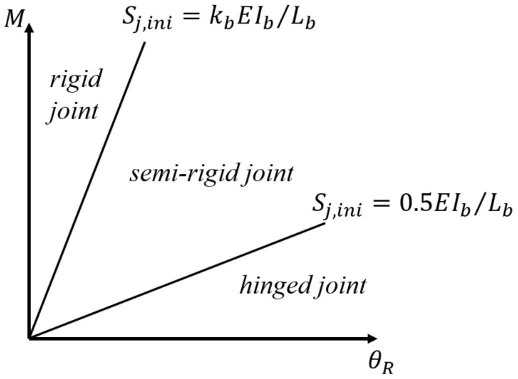

Figure 1. The $M-\theta_R$ curve of semi-rigid connections [6]

2.2. Chinese Standard

The definition and classification of semi-rigid connections in China's Steel Structure Design Standard GB50017-2017 has yet to be systematised, remaining at the conceptual level for the most part [7]. Despite the fact that semi-rigid connections are referenced in the 'Steel Structure Design Standard' GB50017-2017, the classification method is not presented in sufficient detail. Determined through practical experience, China's domestic classification of semi-rigid joints is based on three criteria: the method of connection, joint stiffness and joint force state [8]. Despite their application in practical engineering, these classification methods still require further study and standardisation to provide more precise guidance for design. As the study of semi-rigid connections progresses, it is anticipated that future standards will include more comprehensive and systematic classification methods.

3. Damage Behaviour of Semi-rigid Connections

The study by Yu and Zhu [9] examined the dynamic collapse behaviour of steel frames under rigid, linear semi-rigid and non-linear semi-rigid connections using the finite particle method (FPM). The FPM is capable of simulating planar frames with geometrical nonlinearities and dynamic fracture, and simulates the stiffness of a steel beam-column connection by means of independent zero-length elements. The findings of the numerical examples are corroborated by a comparison with the results of previous studies, including those pertaining to energy conservation. The findings of the study demonstrate that the method offers an efficacious instrument for engineers to examine intricate dynamic fracture issues. The results of the dynamic collapse analysis of the Vogel six-storey frame demonstrate that the semi-rigid connection model has a considerable impact on the structural behaviour. The principal conclusions are as follows:

(1) The rigid connection model may have overestimated both the stiffness and load-carrying capacity of the structure. The rigid connection model exhibits resonance when the frequency of the dynamic force approaches the fundamental natural frequency of the frame. In contrast, the linear and nonlinear semi-rigid connection models do not display such behaviour.

(2) The dissipation of hysteretic damping energy caused by nonlinear connections under dynamic loading is of significant consequence, whereas linear and rigid connections are not. In the context of elastic dynamic fracture, frames with semi-rigid connections demonstrate enhanced collapse resistance relative to those with rigid connections. This is attributed to the capacity of semi-rigid connections to absorb a greater quantity of loading energy and their inherent flexibility.

The findings of this study demonstrate the necessity of contemplating the nature of the connection when designing steel frames, with the objective of enhancing the seismic resilience and security of the structure.

During ductile failure in steel structures, metallic materials experience microporous damage. Modelling this process can assist in the prediction of macroscopic fracture. In a study conducted by Fan et al. [10], the Gurson-Tvergaard-Needleman (GTN) principal model was selected as the primary relationship to investigate the damage evolution and fracture of semi-rigid joints in steel structures, particularly in the context of progressive collapse. The GTN model describes the intrinsic response of metals by deriving a pressure-dependent yield function for isolated spherical pores in a continuous medium. The model simulates the process of microscopic pore formation, growth and merging by defining the pore volume fraction as a damage parameter, thereby effectively predicting the macroscopic fracture behaviour. In this study, the asymptotic collapse of two semi-rigid joints (a steel pipe and an H-beam joint) was simulated using a nonlinear finite element method. The accuracy of the GTN model in simulating the fracture failure of steel semi-rigid joints was validated by a comparison with experimental results. Moreover, a simplified joint failure model is put forth, based on the concentrated plastic hinge theory. This model not only reduces the computational complexity but also fully recovers the node failure characteristics. The principal findings of this study are as follows:

(1) The GTN damage model parameters that can accurately simulate the fracture of metallic materials with microscopic pore formation are obtained through finite element simulation. These microscopic pore aggregation damages are closely related to the macroscopic fracture failure.

(2) The GTN damage model is an effective tool for predicting the failure of semi-rigid joints, providing insights into the internal force changes and deformation information that underpin the

evolution of node performance and damage. The simplified model not only reduces the computational complexity but also fully recovers the characteristics of joint failure.

(3) The FPM method facilitates the simplification of joints at the structural level. Following the removal of the bottom columns at various points, data on internal forces, displacements and other component deformations at pivotal locations can be obtained, reflecting the nonlinear response of the frame structure during progressive collapse. Furthermore, the analysis of fracture and collision between components enables a more accurate prediction of internal forces and a deeper comprehension of structural deformation.

This study presents a streamlined and efficacious methodology for engineering progressive collapse prevention through the GTN model and joint failure model.

4. Load-bearing Characteristics of Different Joints

4.1. End Plate Connection

As shown in Fig. 2, end plate connection is created through the welding of end plates at the extremities of the beams and the affixing of the beams to the columns through the utilisation of high-strength bolts.

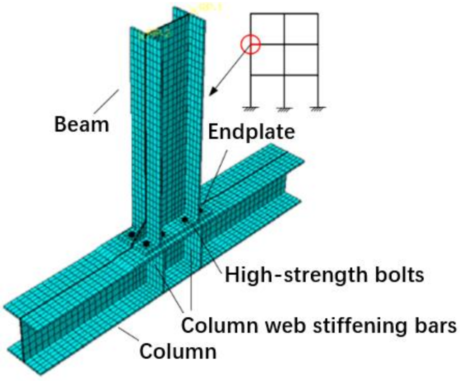

Figure 2. End Plate Connection [11]

The study conducted by Shi et al. [11] reviewed the findings of previous research on the hysteretic properties, energy dissipation behaviour and load-carrying capacity of the joints, with a particular focus on the analysis of semi-rigid joints with end plates. The specimens with end plates extending outward on both sides demonstrate favourable hysteresis characteristics, with the primary energy dissipating element identified as the column web within the joint domain. This energy dissipation capacity is attributed to the plastic development observed within the joint domain. In contrast, the flush end-plate connection exhibited a pronounced decline in stiffness during the loading cycle, accompanied by a notable reduction in hysteretic return characteristics. This resulted in a notable reduction in the flexural load capacity, rotational stiffness, and nodal ductility compared to the extensile node. It is therefore recommended that the extensile end plate connection be used in seismic steel frames, as it can effectively improve the energy dissipation capacity of the joint. The JD3 specimens demonstrated good ductility and ultimate rotation capacity; however, the extensile stiffening ribs of the end plate may reduce the ductility and ultimate rotation capacity of the joint when the bolt diameter is small. It was demonstrated that an increase in the thickness of the end plate results in a reduction in both ductility and energy dissipation capacity. This phenomenon was corroborated by a comparison of JD5 with other specimens.

The hysteresis curves exhibit a degree of discrepancy even when subjected to identical displacement loading. Furthermore, the joint unloading stiffness demonstrates a gradual decline with an increase in the number of hysteresis turns. This suggests that the strength and stiffness of steel may be compromised by repeated loading. The degree of damage is closely correlated with the number of cycles, hysteresis loop area and plastic deformation. This phenomenon has not been sufficiently addressed in the finite element analysis conducted for this study. Consequently, further research is required to investigate the impact of cumulative damage on steel properties.

The maximum load capacities under cyclic loading were typically lower than those observed under monotonic loading, although the differences were not statistically significant. The flexural capacity of the flush end plate connection SC1 was found to be approximately 50% lower than that of the extensile connection. Moreover, the flexural load capacity of specimen SC2 exhibited a decline following the removal of the stiffening ribs in comparison to SC3 and SC4. However, the augmentation of the end plate thickness did not yield a notable impact on the load capacity. It was observed that the joint load-carrying capacity of specimens SC6 and SC7 could be significantly enhanced by increasing the bolt diameter and end plate thickness.

With the exception of the flush endplate joint SC1, the initial stiffnesses of the remaining outrigger endplate joints were found to be similar, indicating that the initial stiffness is not sensitive to local configuration. However, the stiffness of SC1 was reduced by 55%, resulting in a closer alignment with the characteristics observed in the hinged joint. A comparison of nodes with different construction types reveals that semi-rigid joints exhibit load-carrying capacity and initial stiffness comparable to that of stiffened nodes, with minimal loss of performance. This suggests that a well-designed semi-rigid joint can effectively control the force performance to meet engineering requirements.

By establishing a nonlinear finite element calculation model for semi-rigid joints of steel frame end plate connections and combining the results of typical tests conducted domestically and abroad, the following conclusions can be drawn [12, 13]. The extensible semi-rigid joints demonstrate robust performance in terms of load carrying capacity and initial stiffness, whereas the flush joints exhibit a notable decline in these characteristics. The incorporation of judiciously designed stiffening ribs can markedly enhance the energy dissipation capacity of the joint, offering a crucial point of reference for seismic structural design.

4.2. Angle Bar Connection

Angle bar connection is established by the provision of angle bar connectors at the superior and inferior extremities of the beams, as shown in Fig. 3. The Angle is connected with the beam and column respectively, and the beam and column are connected by bolts.

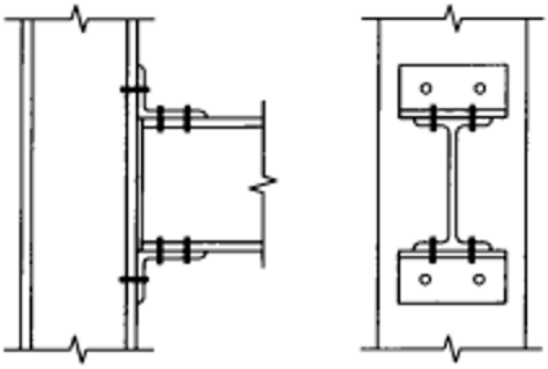

Figure 3. Angle Bar Connection [14]

Xiang [14] examined the influence of various factors on the force performance of upper and lower flange angle bar semi-rigid connections. To this end, an in-depth analysis of their static performance was conducted, and a series of calculation models and theoretical analyses were proposed. This study demonstrates that a multitude of factors influence the bearing capacity of the upper and lower flange angle bar semi-rigid joint, including the thickness of the angle bar, the diameter of the bolts, and their arrangement distance. In particular, the spliced member angle bar is identified as the weak link, which is the first to reach its ultimate load-carrying capacity under the action of a beam end bending moment. It can thus be concluded that the bearing capacity of the joint can be effectively enhanced by increasing the thickness of the angle bar. Furthermore, the distance between the axis of the tension bolt rod and the beam flange has a considerable impact on the static performance of the joint. As this distance increases, the flexural capacity of the joint also declines.

Another crucial parameter is the initial rotational stiffness, which was calculated using the component method in this study. The results indicated that the angle bar thickness and the distance between the bolt axis of the tensioned portion and the back of the angle bar limb had a significant impact on this stiffness. It was demonstrated that an increase in girder height enhances the initial rotational stiffness of the joint, while an expansion in bolt diameter markedly augments both the flexural capacity and the initial rotational stiffness of the joint.

Although this study provides a comprehensive analysis of semi-rigid connections between upper and lower flange angle bars, there are still some unresolved issues that require further investigation. These include the foot-measurement experimental study of the connections, the force performance under dynamic loading and the method of connection design.

The study by Yan [15] is an analysis of the mechanical properties of double web-top-bottom angle bar semi-rigid beam-column joints. In particular, it considers the calculation of the rotational stiffness and the influence of relevant parameters on the performance of the joints in the absence of stiffening ribs. The component method, as set forth in Eurocode 3, was employed as the fundamental analytical approach in the study. This modified method considers the prying force effect and the overhanging chain effect of the angle bar flanges, establishing a corresponding mechanical calculation model.

In this study, the initial tensile stiffness and bearing capacity were obtained by modelling the angle bar with stiffening ribs and without stiffening bars using ABAQUS. The effects of three parameters, namely bolt preload, angle bar stiffening ribs and column web stiffening ribs, on the initial rotational stiffness and load-carrying capacity of the joint were subjected to further analysis, and the optimum range of values for these parameters was summarised. Furthermore, the analysis of various geometrical parameters (e.g., the length-to-height ratio of triangular stiffening ribs, the distance from the bolts on the bent angle limb plate to the tensile angle limb plate, etc.) led to the establishment of a simplified formula suitable for solving the shunt coefficient of the angle bar. This formula was then compared with the simulation results, and it was found that it is applicable and accurate. It should be noted, however, that the study is not without limitations. While a multitude of influencing factors have been taken into account, it is possible that more complex scenarios may arise in actual engineering contexts, such as the effects of nonlinear material behaviour and temperature variations, which have not been fully addressed in this study. Moreover, although the theoretical derivation has been verified by finite element analysis, further experimental validation is still required in practical engineering applications to ensure the reliability of the model. Consequently, in future studies, it is imperative to extend the scope of analysis to encompass a more comprehensive range of working conditions and their influence on joint performance.

4.3. Short T-beam Connection

As shown in Fig. 4, short T-beam connection is established by providing short T-type connectors at the upper and lower extremities of the beams and connecting the connectors to the beams and columns, respectively, with bolts to form beam-column joints.

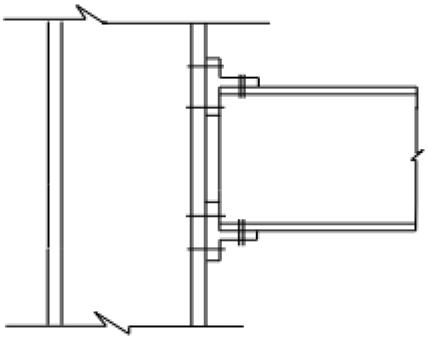

Figure 4. Short T-beam connection [16]

As demonstrated by Fu and Yi [16], the thickness of the T-beam web exerts a considerable influence on the load-bearing capacity of the joint, whereas its impact on rotational stiffness is comparatively limited. At the outset of the loading process, a linear relationship was observed between the moment and the rotation angle of the joint, with minimal discrepancy in initial stiffness. As loading increases, the moment and angle curves of various member joints exhibit inflection points simultaneously, indicating the onset of plastic deformation. Upon continued loading, the joints collectively enter the yielding stage, exhibiting plastic properties. At this stage, the curves can be regarded as parallel curves. It was determined that the ultimate load-carrying capacity of the T-beam web was the lowest when the web thickness was 8 mm. Upon increasing the thickness by 20%, the load-carrying capacity exhibited a 7% increase, while the initial stiffness demonstrated a mere 3.9% rise. This suggests that although an increase in web thickness enhances the joint's ultimate load-carrying capacity and initial stiffness, this effect is not substantial when compared to other influencing factors. This is primarily attributable to the high-strength bolt connection, which results in a larger contact surface friction at the node, thereby enhancing the joint stiffness. The bending moment caused by tensile and compressive forces on the node is also reduced,.

Furthermore, the thickness of both the column flange and the T-beam flange have a considerable impact on the ultimate load-carrying capacity and initial stiffness of the joint. An increase in the thickness of the T-beam flange results in a corresponding enhancement in the ultimate load-carrying capacity and rotational stiffness of the joint. This effect is more pronounced when the column flange is relatively thin; however, when the column flange thickness exceeds two-thirds of the T-steel flange, the effect on the ultimate load-carrying capacity diminishes, while the rotational stiffness continues to exhibit an upward trend. It is therefore recommended that the thickness of the T-steel flange should be 1.3 times that of the column flange.

The variation in height of the T-beam flange has a significant effect on the load-carrying capacity of semi-rigid joint nodes. However, it exerts a relatively lesser influence on initial stiffness. Additionally, the variation of web thickness exerts a degree of influence on the initial rotational stiffness and ultimate load capacity of the joint. The height of the beam section exerts a considerable influence on both the initial stiffness and the ultimate load capacity of the joint. This effect is linear, with an increase in beam height corresponding to an increase in the aforementioned parameters. This phenomenon can be duly considered in the context of the actual project. T-beam semi-rigid joints demonstrate high ductility, effective seismic energy dissipation, and the prevention of brittle damage.

5. Conclusion

The utilisation of steel structures in modern construction has become increasingly prevalent, particularly in the context of bridges, prefabricated buildings and high-rise structures. The distinctive advantages inherent to the material render it the preferred option for the design and construction process. The diversification and aesthetic enhancement of steel structures has become a significant trend in line with the advancement of science and technology and the rising aesthetic standards. Steel possesses a number of advantageous characteristics, including a lightweight composition, high strength, good plastic toughness, and high load-bearing capacity. These properties have significantly accelerated the pace of engineering construction, leading to its widespread adoption in China's construction industry.

In terms of design standards, the European standard EUROCODE 3 defines semi-rigid connections as being between fully rigid and articulated connections, with a certain rotational stiffness and bending moment carrying capacity. In contrast, the definition of semi-rigid connections in China's "Steel Structure Design Standard" GB50017-2017 is not yet systematic and remains at the conceptual level. Further research and standardisation are required to provide clear guidance for design.

Semi-rigid connections demonstrate robust resistance to collapse under dynamic loading conditions. The mechanical damage characteristics of semi-rigid joints are primarily reflected in their nonlinear bending moment-rotation angle relationship and relative flexibility. In response to a load, a semi-rigid connection can transmit a specific bending moment and generate a relative rotation angle, thereby exhibiting a behaviour that is intermediate between that of a fully rigid connection and an ideal hinge. This characteristic results in a reduction in the restraint stiffness of beams on columns, which is a consequence of the joint flexibility of semi-rigid connections. This, in turn, leads to a notable increase in the lateral displacement of the structure. Semi-rigid nodes demonstrate effective energy dissipation capabilities under dynamic loading, effectively absorbing energy during seismic events and enhancing the seismic performance of the overall structure. Furthermore, as the load increases, the rotational stiffness and load-bearing capacity of the nodes will gradually decrease, exhibiting pronounced plastic deformation characteristics.

In terms of the stress characteristics exhibited by different node types, the findings of the study demonstrate that end plate connections, angle steel connections and short T-beam connections each display distinct stress characteristics. End plate connections display favourable hysteretic characteristics, whereas the load-bearing capacity of angle steel connections is subject to influence from a number of factors, including angle steel thickness and bolt diameter. The short T-shaped steel connection demonstrates that the web thickness has a considerable influence on the node bearing capacity, although its impact on the rotational stiffness is relatively minor. Accordingly, in the context of actual design, it is essential to consider these factors in a comprehensive manner with a view to enhancing node performance and structural safety.

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