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Numerical and Theoretical Investigation on the Load-Carrying Capacity of Bolted Ball-Cylinder Joints with High-Strength Steel at Elevated Temperatures

Jianian He\textsuperscript{1}, Baolong Wu\textsuperscript{1}, Nianduo Wu\textsuperscript{2}, Lexian Chen\textsuperscript{1}, Anyang Chen\textsuperscript{3}, Lijuan Li\textsuperscript{1,*}, Zhe Xiong\textsuperscript{1} and Jiaxiang Lin\textsuperscript{1}

\textsuperscript{1} School of Civil and Transportation Engineering, Guangdong University of Technology, Guangzhou 510006, China; jnhe@gdut.edu.cn (J.H.); 2112009068@mail2.gdut.edu.cn (B.W.); chenlexian2022@163.com (L.C.); gdgyxz263@gdut.edu.cn (Z.X.); jxiang.lin@gdut.edu.cn (J.L.)

\textsuperscript{2} China Construction Eight Engineering Division Corp., Ltd., Shanghai 200112, China; cseec8b@csecc.com

\textsuperscript{3} Shantou Polytechnic, Shantou 515071, China; aychen@stpt.edu.cn

* Correspondence: lilj@gdut.edu.cn

Abstract: Bolted ball-cylinder (BBC) joints are suitable for non-purlin space structures to effectively reduce structure height and save material costs. In this paper, we present a numerical and theoretical study for high-strength steel BBC joints at elevated temperatures. An finite element (FE) model was first developed, in which the effects of elevated temperatures were considered by introducing reduction factors for the material properties of steel, such as the yield stress and Young’s modulus, to analyze the structural behavior of BBC joints subjected to compressive, tensile or bending loads. Based on parametric studies on 441 FE models, effects of the key parameters, including joint dimensions, material strength and temperatures, on the structural behavior of BBC joints are discussed. Then, theoretical analysis is conducted, and design methods are proposed to estimate the ultimate load-carrying capacity of BBC joints. Finally, we verified the accuracy of the design method by comparing the prediction with the FE results.

Keywords: bolted ball-cylinder joints; FE analysis; elevated temperature; parametric study; design methods

1. Introduction

Space structure that contains axial members and joints is an efficient structural form to span larger areas without interior supports, such as stadiums and community halls \cite{1-3}. Space structure has the advantages of lightweight, modular construction, high rigidity and cost effectiveness. The mechanical behavior of joints in a space structure is of vital importance for its structural performance. Both welded and assembled joints are commonly used to connect the axial members. Welded joints such as welded tubular joints and welded spherical joints \cite{4} are ideally assumed as rigid. Nevertheless, assembled joints generally exhibit a semi-rigid behavior. Up to now, various types of assembled joints, such as bolted-ball joints \cite{5}, socket joints \cite{6} and plate joints \cite{7}, have been invented and investigated.

Ahmadizadeh and Maalek \cite{6} investigated the effect of socket joint flexibility on space structure behavior and found that node deformability resulted in significant changes in member forces, structure stiffness and load-carrying capacity. Ebadi-Jamkhaneh and Ahmadi \cite{8} conducted an experimental and numerical study on MERO joints to investigate the effect of bolt tightness on the joint axial behavior. Han et al. \cite{9} investigated the compressive behavior of a novel assembled hub joint in single-layer latticed domes and proposed theoretical models to predict the axial stiffness and strength. Xiong et al. \cite{7,10} studied the behavior of single-layer reticulated shells with gusset joints and found that the semi-rigid behavior of joints has a significant influence on the buckling behavior of the
single-layer shells. In general, the behavior of joints greatly affects the performance of a space structure.

In recent years, a new joint type named the bolted ball-cylinder (BBC) joint was proposed for non-purlin space structures [11]. In this structure, roof boards can be directly placed on the upper chords to effectively reduce the structural height and save costs. A bolted ball-cylinder joint consists of a solid semi-sphere and a circular tube. The chords, which are commonly in a rectangular tubular shape, are connected to the circular tube by bolts, and the diagonal members can be connected to the solid semi-sphere [12]. Zeng et al. [13] conducted experimental and numerical studies on the BBC joints subjected to tensile or compressive loads. They found that the strength of the circular tube mainly controlled the load-bearing capacity of the joints.

In recent decades, extensive high-performance and novel constructional materials have been applied to civil engineering [14–17], such as fiber-reinforced polymer, seawater sea sand concrete and high-strength aluminum. For steel structures, with the development of manufacturing techniques, using high-strength steel up to 1000 MPa is a trend in future construction for the efficient utilization of materials. Although several studies have been conducted for BBC joints, their structural behavior at elevated temperatures has not been investigated. It is known that design for fire resistance is a key requirement for steel structures [18]. Elevated temperatures could deteriorate the material properties such as the yield stress and Young’s modulus of steel [19,20]. In current design standards (e.g., EC3 [21] and GB 51249 [22]), reduction factors are specified for the yield strength and Young’s modulus of steel to account for the effect of elevated temperatures. Although no finite element (FE) studies have been conducted for BBC joints at elevated temperatures, some FE studies have been reported for steel joints at elevated temperatures, such as beam-to-column joints [23], T-joints [24,25] and tubular T-T joints [26].

In order to fill the knowledge gap of the structural behavior of BBC joints made of high-strength steel at elevated temperatures and promote the application of the novel BBC joints, we present here a numerical and theoretical study on BBC joints subjected to various loading scenarios, including compression, tension and bending. An FE model that accounts for the effect of temperatures was developed and verified. Based on FE analysis, parametric study was conducted for joints subjected to various temperatures and loading types to investigate the effects of key parameters on the structural behavior (i.e., strength, stiffness and load–displacement curves) of BBC joints. Finally, we propose design methods for the joints at elevated temperatures.

2. Finite Element Model
2.1. BBC Joint at Ambient Temperature

A bolted ball-cylinder (BBC) joint consists of a circular tube, a solid hemisphere, concave washers, bolts, end plates and tubular beams as shown in Figure 1, where $D$, $t$ and $H$ are the diameter, thickness and height of the circular tube, respectively; and $b_1$ and $H_0$ are the width and height of the tubular beam, respectively. A schematic diagram of each part in a BBC joint is shown in Figure 2. The FE model for a BBC joint at ambient temperature was simulated by the commercial FE software ABAQUS [27].

![Figure 1. Bolted ball-cylinder joint.](Image)
Solid element C3D8I was used for the tubular beams and C3D8R was adopted for all the other components. All the parts were meshed by swept or structural meshing techniques to generate hexahedra-shaped elements (Figure 3). The element size for the model was selected as 5 mm, except the element size for the loading tube was 1.5 mm. This mesh size could achieve a balance between analysis accuracy and computing time. The classic metal plasticity model in ABAQUS (Dassault Systemes Simulia Corp. Johnston, RI, USA) was adopted for steel components. This material model implements the von Mises yielding criterion with an isotropic hardening feature. An elastic-perfect plastic model was used for bolts whereas the other components of the joint were modelled by a tri-linear model. The parameters for the material model were obtained from the tensile coupon test in [11], which was conducted in accordance with GB/T 228.1-2010 [28]. The measured yield strength ($f_y$), ultimate strength ($f_u$) and Young’s modulus ($E_S$) are 215.7 MPa, 589.7 MPa and 209.5 GPa, respectively. Specially, the tri-linear model consists of a linear elastic portion up to $f_y$, a hardening portion up to $f_u$ with hardening modulus of 0.05 $E_s$ and a perfect plastic portion with constant stress of $f_u$. The high-strength bolt was 10.9 grade with nominal yield strength of 900 MPa and ultimate strength of 1000 MPa. For the supporting plate, loading tube and loading plate, the material is set as elastic with a very high modulus of 1000 times of steel Young’s modulus.
Figure 3. Finite element (FE) model of BBC joint under bending.

Contact was defined in the FE model to simulate the interactions between components (e.g., circular tube, washers and bolts) that prevent penetration but allow separation between them. Contact between the components was defined by “surface-to-surface” contact pairs. “Hard” contact was defined in the normal direction and the penalty friction with small sliding was applied for the tangential direction. The friction coefficient was set as 0.2 and the other parameters were set as default. Depending on the loading scenarios (i.e., compression, tension or bending), boundary conditions were applied on the supporting plates and displacements were applied on the loading plates.

Six analysis steps were added to the FE model for a smooth establishment of the pretension load in bolts and the contacts. The steps were as follows: apply temporary restraints and small force (i.e., 10 N) in bolts; remove the temporary restraints; set boundary conditions and a small displacement of 0.001 mm; modify the force in bolt as 5 kN; fix the bolt length; apply the actual displacement. The analysis was determined due to excessive deformation of the joint that led to a convergency difficulty. Nevertheless, the convergency problem occurred at a very late stage of the loading process and the ultimate capacity could be reached. After completing the analysis, load–displacement curves were obtained by extracting the reaction forces. It is necessary to mention that the preload in bolts is very low to simulate the snug tight condition of the bolts during experiments.

2.2. Verification of FE Model at Ambient Temperature

Three specimens from [11], which were JD5 under compression, JD8 under tension and JD10 under positive bending, were selected to verify the FE model. The dimensions of the specimens for JD5, JD8 and JD10 are $D = 140, 180$ and $160$ mm; $t = 10, 8$ and $8$ mm; and $H = 140, 120$ and $140$ mm, respectively. Size of the tubular beams is $120 \times 60 \times 5$ mm for all the specimens. As shown in Figure 4, concentrical load was applied on the end plate of tubular beams for specimen JD5 and JD8, whereas the load was applied on the endplate of the loading tube. The layout of LVDTs (Linear Variable Displacement Transducers) for the specimens is shown in Figure 4. The recorded displacement for compressive and tensile specimens (i.e., JD5 and JD8) is taken as the relative displacement between point A and A’ (Figure 4). For specimen JD10 under positive bending, the recorded displacement is the average displacement at points B and B’ subtracted by the average displacement at points C and C’. From FE analysis, the simulated deformed shapes of BBC joints agree well with the experimental observations. The difference in the load–displacement curves obtained from FE analysis and the experimental results is generally less than 10%, as shown in Figure 5. Therefore, the FE model could accurately simulate the structural behavior of BBC joints at the ambient temperature.
2.3. FE Model Considering Engineering Practice

For experimental specimens in [11], the end plates of the tubular beams were fixed to the actuator and the beam was short. The additional restraints from loading plates led to an increase in the load-carrying capacity. However, in engineering projects, the tubular beam is long and the restraint from the beams is weaker than in the experiment. Based on FE analysis, the additional restraints caused a significant increase in the compressive capacity. Therefore, in parametric study, the loading plates were removed to better simulate the real behavior of the joints in structures.

In the design method for steel structures, yield strength is commonly used as the strength parameter. It is more reasonable to use the elastic-perfect plastic model in FE analysis for a convenient derivation of design methods. It was found that the ultimate capacity of BBC joints adopting elastic-perfect plastic model is lower than that adopting the tri-linear model. Therefore, the derived design method based on the elastic-perfect plastic model has safety margins to some extent. In the parametric study, the elastic-perfect plastic model was adopted for the FE model.

2.4. Constitutive Model for Steel at Elevated Temperature

It is known that the material properties of steel are degraded at elevated temperatures. In the “Code for fire safety of steel structures in buildings” [22], reduction factors $\eta_T$ and $\chi_T$ are introduced to account for the effects of elevated temperatures on the yield strength and Young’s modulus of steel, respectively. Yield strength $f_{y,T}$ and Young modulus $E_T$ could be determined by Equations (1) and (2), respectively:

$$\eta_T = \frac{f_{y,T}}{f_y} = \begin{cases} 
1.0 & 20 \, ^{\circ}C \leq T \leq 300 \, ^{\circ}C \\
1.24 \times 10^{-8}T^3 - 2.096 \times 10^{-5}T^2 + 9.288 \times 10^{-3}T - 0.2168 & 300 \, ^{\circ}C < T < 800 \, ^{\circ}C \\
0.5 - \frac{T}{2000} & 800 \, ^{\circ}C \leq T \leq 1000 \, ^{\circ}C
\end{cases}$$

(1)
\[ \chi_T = \frac{E_T}{E} = \begin{cases} \frac{7T - 4780}{1000 - 1} & 20 \degree C \leq T < 600 \degree C \\ \frac{6T - 2800}{6T - 2000} & 600 \degree C \leq T \leq 1000 \degree C \end{cases} \] (2)

Where \( f_y \) is the yield strength and \( E \) is the Young’s modulus of steel at ambient temperature, and \( T \) is the temperature in \( \degree C \).

Current standards do not cover the behavior of high-strength bolts in fire. Based on the study in [29], the reduction in the yield strength (\( f_{y,\text{bolt},T} \)) and Young’s modulus (\( E_{\text{bolt},T} \)) of high-strength bolts (10.9 grade) at elevated temperatures could be estimated by Equations (3) and (4), respectively:

\[ \lambda_T = \frac{f_{y,\text{bolt},T}}{f_{y,\text{bolt}}} = 4 \times 10^{-9}T^3 - 6 \times 10^{-6}T^2 + 0.0011T + 0.9603 \] (3)

\[ \omega_T = \frac{E_{\text{bolt},T}}{E_{\text{bolt}}} = 6 \times 10^{-9}T^3 - 8 \times 10^{-6}T^2 + 0.0016T + 0.9433 \] (4)

Where \( f_{y,\text{bolt}} \) and \( E_{\text{bolt}} \) are the yield strength and Young’s modulus of high-strength bolts at ambient temperature. Figure 6 and Table 1 show the reduction factors for the yield strength and Young’s modulus of steel and high-strength bolts at elevated temperatures.

![Figure 6. Reduction factors for steel and high-strength bolts at elevated temperatures.](image)

| \( T (\degree C) \) | Steel | High-Strength Bolt |
|----------------|-------|---------------------|
| 20             | 1.00  | 1.00                |
| 100            | 0.98  | 1.00                |
| 200            | 0.95  | 1.00                |
| 300            | 0.91  | 0.97                |
| 400            | 0.84  | 0.86                |
| 500            | 0.73  | 0.71                |
| 600            | 0.50  | 0.45                |

3. Parametric Study

3.1. Specimens

As shown in Figure 7, four types of loads on BBC joints were investigated in the current study, which are compression (denoted as “CN” joint), tension (“TN”), positive bending (“BN”) and negative bending (“RBN”). The key parameters affecting the structural behavior of BBC joints include the outer diameter (\( D \)), thickness (\( t \)) and height (\( H \)) of the circular tube, and the width (\( b_1 \)) and height (\( H_0 \)) of the tubular beam (Figure 1). Twenty-one FE joints were developed for parametric study to cover these key parameters, as shown in Table 2. For each joint, seven temperatures (i.e., 20 °C, 100 °C, 200 °C, 300 °C, 400 °C, 500 °C and 600 °C)
and three steel strengths (i.e., Q235, Q345 and Q690 steel with $f_y = 235$ MPa, $345$ MPa and $690$ MPa, respectively) were selected, yielding a total of 441 FE models, to investigate the structural behavior of BBC joints at elevated temperatures. Due to the limitation of article length, the results of Q690 joints are reported in the following subsections and Q235 and Q345 joints exhibited a similar trend as that of Q690 joints.

![Figure 7. Loading scenarios for BBC joints.](image)

### Table 2. Joints for parametric study.

| Joint No. | Variable | $D$ (mm) | $t$ (mm) | $H$ (mm) | $b_1$ (mm) | $b_2$ (mm) | $H_0$ (mm) |
|-----------|----------|----------|----------|----------|------------|------------|------------|
| N1        | N/A      | 150      | 10       | 160      | 60         | 26         | 120        |
| N2        | $D$      | 110      | 10       | 160      | 60         | 26         | 120        |
| N3        |          | 130      | 10       | 160      | 60         | 26         | 120        |
| N4        |          | 170      | 10       | 160      | 60         | 26         | 120        |
| N5        |          | 190      | 10       | 160      | 60         | 26         | 120        |
| N6        | $t$      | 150      | 8        | 160      | 60         | 26         | 120        |
| N7        |          | 150      | 9        | 160      | 60         | 26         | 120        |
| N8        |          | 150      | 11       | 160      | 60         | 26         | 120        |
| N9        |          | 150      | 12       | 160      | 60         | 26         | 120        |
| N10       | $H$      | 150      | 10       | 120      | 60         | 26         | 120        |
| N11       |          | 150      | 10       | 130      | 60         | 26         | 120        |
| N12       |          | 150      | 10       | 140      | 60         | 26         | 120        |
| N13       |          | 150      | 10       | 150      | 60         | 26         | 120        |
| N14       | $b_1$    | 150      | 10       | 160      | 50         | 26         | 120        |
| N15       |          | 150      | 10       | 160      | 55         | 26         | 120        |
| N16       |          | 150      | 10       | 160      | 65         | 26         | 120        |
| N17       |          | 150      | 10       | 160      | 70         | 26         | 120        |
| N18       | $H_0$    | 150      | 10       | 160      | 60         | 26         | 130        |
| N19       |          | 150      | 10       | 160      | 60         | 26         | 140        |
| N20       |          | 150      | 10       | 160      | 60         | 26         | 150        |
| N21       |          | 150      | 10       | 160      | 60         | 26         | 160        |

### 3.2. Joints under Compression

Load–displacement curves of a typical Q690 specimen N1 under compression with various temperatures are plotted in Figure 8. For joints subjected to temperatures less or equal than 300 °C, the curves are almost identical, indicating that the temperature effect is insignificant. With further increase in the temperature, the initial stiffness and ultimate compressive capacity of a joint decrease gradually. In general, the shapes of the load–displacement curves of the joints subjected to various temperatures are similar. Similar trends could be found for all the other joints (i.e., N2–N21).
Figure 8. Effects of elevated temperatures on the load–displacement curves of specimen N1 under compression: (a) load–displacement curves; (b) failure process; (c) deformed shape corresponding to point C.

By examining the deformed shapes and stress contours of the joints under various temperatures, the failure mechanisms are similar to those under ambient temperature. Due to compression, the free end of the circular tube in a joint first yields, and the yield zone extends to the hemisphere. At the ultimate load, complete yielding of the free end is observed, and plastic hinges are formed at the tube faces connected to the tubular beams. After the peak load, the applied load decreases slowly. Figure 8b shows the failure process of specimen N1 at 600 °C. The deformed shape of the joint at ultimate load is shown in Figure 8c.

Based on FE analysis, key parameters affecting the structural behavior of a BBC joint include the outer diameter, thickness and height of the circular tube and the width and height of the tubular beam. Parametric studies were conducted to investigate the effects of these key parameters on the initial stiffness and ultimate capacity of Q690 BBC joints, as shown in Figures 9 and 10, respectively. The initial stiffness is defined as the slope of the load–displacement curve in the elastic region. In this paper, it is equal to the slope of the line between the origin and point A as shown in Figure 8b, where the load at point A is generally a quarter to a third of the peak load. The ultimate capacity is defined as the peak load during the loading process (i.e., point C in Figure 8b).

Figure 9. Effects of parameters on the initial stiffness of BBC joints under compression: (a) outer diameter of the tube; (b) thickness of the tube; (c) height of the tube; (d) width of the tubular beam; (e) height of the tubular beam.
Figure 10. Effects of parameters on the load-carrying capacity of BBC joints under compression: (a) outer diameter of the tube; (b) thickness of the tube; (c) height of the tube; (d) width of the tubular beam; (e) height of the tubular beam.

With the increase in the outer diameter of the tube, both the initial stiffness and ultimate capacity decrease dramatically first, and then the decreasing rate slows down, as a tube with a larger diameter is more prone to local buckling. Comparison between Figures 9a and 10a indicates that the effect of the outer diameter is more prominent on the initial stiffness than that on the ultimate capacity. A thicker tube also leads to an enhancement in the initial stiffness and ultimate capacity. However, increasing the height of the tube has an opposite effect. Furthermore, an increase in the beam size (i.e., width and height) leads to a gradual increase in the initial stiffness and the ultimate capacity since the stress concentration on the tube wall is less severe. As expected, an elevated temperature reduces the initial stiffness and ultimate capacity of the joint due to the deterioration in material properties. Nevertheless, if the temperature is lower than 300 °C, the negative effect of temperature is insignificant.

3.3. Joints under Tension

Figure 11 plots the load–displacement curves of Q690 specimen N1 under tension with various temperatures. In general, obvious strain hardening is observed for joints under tension as the joint capacity is mainly controlled by material strength. When the temperature is higher than 400 °C, significant reductions in the initial stiffness and the capacity are observed. Nevertheless, the failure modes of the joint under ambient and elevated temperatures are similar, which is a successive yielding of the circular tube. As the applied load did not drop during the loading process, the load at point C in Figure 11b is defined as the ultimate capacity. The ultimate load corresponds to a complete yielding of the circular tube (Figure 11b). From this point, the slope of the load–displacement curve remains constant. The deformed shape of the joint at ultimate load is shown in Figure 11c.
Effects of the key parameters on the initial stiffness and ultimate capacity of Q690 BBC joints are shown in Figures 12 and 13, respectively. With the increase in the outer diameter of the tube, the initial stiffness and ultimate load decrease first and keep almost consistent if the diameter is larger than 170 mm. The initial stiffness and ultimate capacity increase gradually with the increase in tube thickness or with the decrease in tube height. The width of tubular beams does not notably affect the structural behavior of a joint, as shown in Figures 12d and 13d. With the increase in the tubular beam height, the initial stiffness increases slightly, but its effect on the ultimate capacity is insignificant.

Figure 12. Effects of parameters on the initial stiffness of BBC joints under tension: (a) outer diameter of the tube; (b) thickness of the tube; (c) height of the tube; (d) width of the tubular beam; (e) height of the tubular beam.
Figure 13. Effects of parameters on the load-carrying capacity of BBC joints under tension: (a) outer diameter of the tube; (b) thickness of the tube; (c) height of the tube; (d) width of the tubular beam; (e) height of the tubular beam.

3.4. Joints under Positive Bending

Figure 14 shows the effects of elevated temperatures on the load–displacement curves of Q690 specimen N1 under positive bending. Similar to the joints under tension, the applied load did not drop during the loading process, and the ultimate load is defined as the load at point C in Figure 14b. The deformed shape of the joint at ultimate load is shown in Figure 14c. If the temperature is less than 300 °C, the effect of temperature on joint behavior is insignificant. However, with a further increase in temperature, both initial stiffness and ultimate capacity deteriorate dramatically. Failure mode of the joint at an elevated temperature is similar as that at ambient temperature, in which plastic hinges are formed at the tube-to-beam junctions.

As shown in Figure 15, the initial stiffness of Q690 joints increases with the increase in tube thickness and the tubular beam height. Increasing the outer diameter of the tube leads to a reduction in the initial stiffness as the tube is more prone to buckling. Nevertheless, the effects of tube height and tubular beam width on the initial stiffness are insignificant. For the ultimate capacity shown in Figure 16, effects of tube diameter, tube height and beam
width are insignificant. The ultimate capacity is enhanced by increasing the tube thickness and the height of the tubular beams.

![Figure 15](image1.png)  
**Figure 15.** Effects of parameters on the initial stiffness of BBC joints under positive bending: (a) outer diameter of the tube; (b) thickness of the tube; (c) height of the tube; (d) width of the tubular beam; (e) height of the tubular beam.

![Figure 16](image2.png)  
**Figure 16.** Effects of parameters on the load-carrying capacity of BBC joints under positive bending: (a) outer diameter of the tube; (b) thickness of the tube; (c) height of the tube; (d) width of the tubular beam; (e) height of the tubular beam.

### 3.5. Joints under Negative Bending

For Q690 joints under negative bending, the effects of elevated temperatures on the load–displacement curves are illustrated in Figure 17. The applied load almost keeps constant after reaching the peak load and the ultimate load is defined as the peak load.
(i.e., point C in Figure 17b). The deformed shape of the joint at ultimate load is shown in Figure 17c. Similar to joints under positive bending, the adverse effect of elevated temperatures on the joint behavior becomes obvious when the temperature is higher than 400 °C. For a given joint, the ultimate capacity under negative bending is lower than that under positive bending, as the free end of the circular tube is prone to local buckling.

Figure 17. Effects of elevated temperatures on the load–displacement curves of specimen N1 under negative bending: (a) load–displacement curves; (b) failure process; (c) deformed shape corresponding to point C.

As shown in Figure 18, the initial stiffness decreases with the increase in the outer diameter of the tube or with the decrease in tube thickness. The effect of tube height on the initial stiffness is insignificant. A slight increase in the initial stiffness is observed when increasing the beam size (i.e., width and height). Figure 19 shows the effect of the key parameters on the ultimate capacity. In general, an increase in tube thickness or beam width leads to an increase in the ultimate capacity. However, the influences of other parameters such as tube diameter, tube height and beam height on the ultimate capacity are insignificant.

Figure 18. Effects of parameters on the initial stiffness of BBC joints under negative bending: (a) outer diameter of the tube; (b) thickness of the tube; (c) height of the tube; (d) width of the tubular beam; (e) height of the tubular beam.
Figure 19. Effects of parameters on the load-carrying capacity of BBC joints under negative bending: (a) outer diameter of the tube; (b) thickness of the tube; (c) height of the tube; (d) width of the tubular beam; (e) height of the tubular beam.

4. Theoretical Analysis

4.1. Effects of Elevated Temperatures on the Capacities of BBC Joints

Based on parametric studies, the reduction in the ultimate capacity of a joint at elevated temperatures has a similar trend to the yield strength reduction of steel, regardless of the loading scenario. Therefore, the ultimate capacity of a joint at elevated temperatures could be predicted using the formulas for ambient temperature, but replacing the material properties at ambient temperature with those at elevated temperatures.

4.2. Design Method

Based on FE analysis, plastic hinges were formed in the circular tube. For a circular tube under compression or tension, plastic hinges first appeared at the loaded beam-to-tube junctions (location 1 in Figure 20) and then formed at location 2. The ultimate load was achieved when plastic hinges were formed at location 2.

Figure 20. Plastic hinges formed in the circular tube (location 1 and 2): (a) under compression; (b) under tension.

For a joint, owing to the constraints provided by washers and end plates, rigid parts were formed in the circular tube, shown as the dark areas in Figure 21a. The length of the rigid part is equal to the width of the tubular beams (i.e., \( b_1 \) for the loaded beams and \( b_2 \) for
the beams perpendicular to the loaded beams). At ultimate load, plastic hinges are formed, and the tube wall is completely yielded. Based on mechanics (Figure 21b), bending moment at plastic hinges is:

\[ M_u = \frac{F}{4}(l_1 + \frac{t}{2}) \]  

and the plastic moment capacity is:

\[ M_u = \frac{H_0 l_2 f_{y,T}}{4} \]  

where \( f_{y,T} \) is the yield strength at elevated temperature that can be calculated from the yield strength at ambient temperature by Equation (1), \( H_0 \) is the height of the tubular beam, and \( l_1 \) is calculated by Equation (7):

\[ l_1 = \sqrt{\left(\frac{D}{2} - t\right)^2 - \frac{b_2^2}{4} - \frac{b_1^2}{4}} \]  

By combining Equations (5)–(7), the ultimate capacity of a BBC joint under compression could be determined as:

\[ F_1 = \alpha \frac{2H_0 l_2 f_{y,T}}{2\left(\sqrt{\left(\frac{D}{2} - t\right)^2 - \frac{b_2^2}{4} - \frac{b_1^2}{4}} + t\right)} \]  

where \( \alpha \) is a coefficient accounting for the discrepancy between experimental (or FEM) results and theoretical derivations.

![Figure 21. Analytical model for BBC joint capacity: (a) geometry; (b) under compression; (c) under positive bending.](image)

Based on the parametric study on BBC joints with various steel grade in Section 3, \( \alpha \) depends on the key parameters of a BBC joint, including the diameter \( D \), height \( H \), thickness \( t \) of the circular tube, and the width \( b_1 \) and height \( H_0 \) of the tubular beam. By regression analysis, the coefficient \( \alpha \) is calculated by Equation (9) for Q235, Q345 and Q690 steel.

\[ \alpha = \begin{cases} 
7.528 \times 10^{-2} D^{1.703} t^{-0.625} H^{-0.401} b_1^{-0.210} H_0^{-0.199}, & \text{for Q235} \\
6.494 \times 10^{-2} D^{1.684} t^{-0.612} H^{-0.408} b_1^{-0.193} H_0^{-0.171}, & \text{for Q345} \\
4.767 \times 10^{-2} D^{1.584} t^{-0.530} H^{-0.450} b_1^{-0.108} H_0^{-0.098}, & \text{for Q690} 
\end{cases} \]  

(9)
The ultimate capacity of a BBC joint under tension could be derived in a similar pattern as the joint under compression. The ultimate capacity \( F_2 \) could be calculated by Equation (10) and the parameter \( \beta \) is determined by Equation (11) for various steel grades.

\[
F_2 = \beta \frac{2H_0^2 f_y T}{2(\sqrt{\frac{D}{2}} - t)^2 - \frac{b_1}{2} - \frac{b_2}{2}} + t
\]

\[
\beta = \begin{cases} 
9.957D^{1.421}t^{-0.541}H^{-0.403}b_2^{-0.216}H_0^{-0.929}, & \text{for Q235} \\
6.896D^{1.583}t^{-0.802}H^{-0.407}b_2^{-0.247}H_0^{-0.879}, & \text{for Q345} \\
11.103D^{1.495}t^{-1.339}H^{-0.337}b_2^{-0.174}H_0^{-0.780}, & \text{for Q690}
\end{cases}
\]

where the definitions of the symbols are the same as those in the previous formulas.

For a joint under bending, force couple is formed in the joint. Owing to the existence of the hemisphere, failure of the free end of the circular tube governs the ultimate capacity. As shown in Figure 21c, the moment capacity for the joint under positive bending could be calculated from the tensile capacity of the circular tube:

\[
M_1 = \gamma \frac{2H_0^2 f_y T}{2(\sqrt{\frac{D}{2}} - t)^2 - \frac{b_1}{2} - \frac{b_2}{2}} d_b
\]

\[
\gamma = \begin{cases} 
4.803 \times 10^{-4}D^{1.800}t^{-0.671}H^{-0.358}b_1^{-0.039}H_0^{-0.634}, & \text{for Q235} \\
5.291 \times 10^{-4}D^{1.844}t^{-0.766}H^{-0.422}b_1^{-0.003}H_0^{-0.641}, & \text{for Q345} \\
1.860 \times 10^{-3}D^{1.729}t^{-1.190}H^{-0.496}b_1^{-0.024}H_0^{-0.723}, & \text{for Q690}
\end{cases}
\]

where \( d_b \) is the distance between the top and bottom bolt rows. Similarly, the ultimate moment capacity of a joint under negative bending is controlled by the compressive failure of the free end of the circular tube, which could be calculated as:

\[
M_2 = \eta \frac{2H_0^2 f_y T}{2(\sqrt{\frac{D}{2}} - t)^2 - \frac{b_1}{2} - \frac{b_2}{2}} d_b
\]

\[
\eta = \begin{cases} 
0.207D^{1.885}t^{-0.803}H^{-0.172}b_2^{-0.321}H_0^{-0.712}, & \text{for Q235} \\
0.207D^{1.885}t^{-0.803}H^{-0.172}b_2^{-0.321}H_0^{-0.712}, & \text{for Q345} \\
0.250D^{1.885}t^{-0.880}H^{-0.206}b_2^{-0.280}H_0^{-0.736}, & \text{for Q690}
\end{cases}
\]

where the definitions of the symbols are the same as those in the formulas for positive bending capacity.

4.3. Verification of the Design Method

In order to verify the design method, four FE specimens were selected, and their dimensions are listed in Table 3. For each specimen, four loading scenarios (i.e., compression, tension, positive bending and negative bending) and seven temperatures, 20 °C, 100 °C, 200 °C, 300 °C, 400 °C, 500 °C and 600 °C, were adopted. A comparison between the predicted ultimate capacity and FE capacity is shown in Figure 22, which indicates an adequate match between them. In general, the average ratios of predicted-to-FE capacity are 0.95, 0.98, 0.97 and 0.95 for BBC joints under compression, tension, positive bending and negative bending, respectively, and the corresponding coefficients of variation (COV) are 0.01, 0.03, 0.05 and 0.03, respectively. Therefore, the proposed design method could reasonably predict the ultimate capacity of BBC joints at elevated temperatures.
Table 3. Verification of the proposed design method.

| Specimen | D (mm) | t (mm) | H (mm) | b₁ (mm) | H₀ (mm) |
|----------|--------|--------|--------|---------|--------|
| EJ1      | 130    | 8      | 120    | 60      | 120    |
| EJ2      | 170    | 12     | 120    | 60      | 120    |
| EJ3      | 130    | 8      | 150    | 60      | 120    |
| EJ4      | 170    | 12     | 150    | 60      | 120    |

Figure 22. Verification of the design method: (a) compressive and tensile capacities; (b) bending capacities.

5. Conclusions

Based on FE and theoretical analysis of high-strength steel BBC joints at elevated temperatures, the following conclusions could be drawn:

1. By comparing to experimental results, the FE model developed in this study is reasonable and accurate. A refined FE model was developed to account for the influence of loading plates on joint behavior and the effect of elevated temperature on steel material properties.

2. If the temperature is equal to or lower than 300 °C, its effects on the initial stiffness and ultimate capacity of joints are insignificant. Nevertheless, with a further increase in temperature, the initial stiffness and ultimate capacity notably deteriorate.

3. Effects of circular tube size (i.e., thickness, diameter and height) in a joint and beam size (i.e., height and width) on the initial stiffness and ultimate capacity of BBC joints are investigated. In general, reducing the height and increasing the thickness of the circular tube have significant effects on enhancing the initial stiffness and ultimate capacity.

4. Design methods are proposed to estimate the ultimate capacity of BBC joints at elevated temperatures. Verification shows that the design method has suitable accuracy for joints under the loading scenarios of compression, tension, positive bending and negative bending.

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