Engineering Structures 165 (2018) 457–470

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

# Experimental and numerical study on ultimate behaviour of high-strength steel tubular K-joints with external annular steel plates on chord circumference

Song-Zhao Qu[a,b], Xiao-Hong Wu[c], Qing Sun[a,*]

[a] *Department of Civil Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China*
[b] *Henan Electric Power Survey & Design Institute, Zhengzhou, Henan 450007, China*
[c] *School of Aerospace, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China*

ARTICLE INFO

*Keywords:*
Circular hollow section
Q690 High-strength steel
Ultimate strength
Tube-gusset connection
Virtual work principle
External annular steel plate

ABSTRACT

This study presents experimental and numerical studies on the ultimate behaviour of K-joints in transmission tubular structures. Tests were conducted on nine connection specimens using high-strength steel to investigate ultimate strength. The material properties and load–displacement responses of nine tubular K-joints are tested and discussed with emphasis on the factors that affect the ultimate strength of the joints. Based on the experimental and numerical results, the failure mode and mechanism of the high-strength steel K-joints are identified. Using energy theory and the virtual work principle, a formula for predicting the ultimate strength of high-strength steel K-joints is developed. In order to verify the validity of the proposed formula, finite element models are built to perform a sensitivity analysis on the parameters that affect the ultimate strength of the connections. The results indicate that the compression ratio of the chord and the thickness and diameter of the chord have significant effects on the ultimate strength of the K-joints with an external annular steel plate. Moreover, the results predicted by the proposed formula correlated very well with the experimental and numerical results.

## 1. Introduction

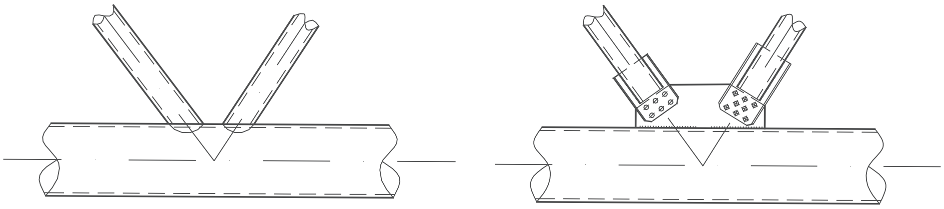
Tubular members have been used as the chords and bracing members in the 1000 kV high-voltage and large-span electric transmission towers in China. These members exhibit effective structural performance in a small windward area, and have a large gyration radius, simple structure, clear power transmission path and low steel consumption. However, the joints in tubular steel towers are highly complex and diverse because they comprise numerous members connected from different directions. Furthermore, the stress distribution in a joint is very complex. Once the internal force of a connection exceeds the ultimate strength of that connection, the force transmission path will change, which leads to failure of the entire structure. Therefore, joint connections are important parts of tubular steel towers and require careful design. For tubular transmission towers, two main joint types exist: (a) the tubular joint, and (b) the tube-gusset joint, as illustrated in Fig. 1. The tube-gusset joint generally consists of bracing members, a chord, gusset plate and annular plates, as indicated in Fig. 2. The gusset plate is welded onto the chord tube wall and bolts are used to connect the bracing members to the gusset plate. In practice, the chord and bracing members generally carry the axial load, as these are subjected to axial compressive and tensile forces. The tube-gusset joint connection is easier to construct than the tubular joint.

Several experimental and numerical studies have been conducted over the past few decades in order to develop formulae for determining the ultimate strength of normal-strength steel tubular joints. Saeko [1] developed a formula that yields a conservative estimation of the ultimate strength of K-, TY- and X-shaped joints. Kurobane [2] and Werdenier [3] developed a formula for calculating the ultimate strength of TP and XP joints. Soh [4] and Bao [5] conducted a simple theoretical analysis using the yield line model and virtual work principle in order to determine the ultimate strength of tube-gusset plate joints. Dexter and Lee [6,7] investigated overlapping K-joints and developed formulae for the ultimate strength of this joint type. Kim [8] conducted tests for K-type tube-gusset plate joints and developed a formula for calculating the axial brace forces and ultimate moment on the joints. Feng and Young [9] performed tests for T and X cold-formed stainless-steel tubular joints, and the developed formulae are more accurate and reliable than current design results. Wang and Guo [10] experimentally and numerically investigated the behaviour of a tube-gusset K-joint, and

---

[*] Corresponding author.
*E-mail address:* sunq@mail.xjtu.edu.cn (Q. Sun).

https://doi.org/10.1016/j.engstruct.2018.03.025
Received 6 November 2017; Received in revised form 5 March 2018; Accepted 11 March 2018
0141-0296/



(a) Tubular joint

(b) Tube-gusset joint

**Fig. 1.** Tube joint types.

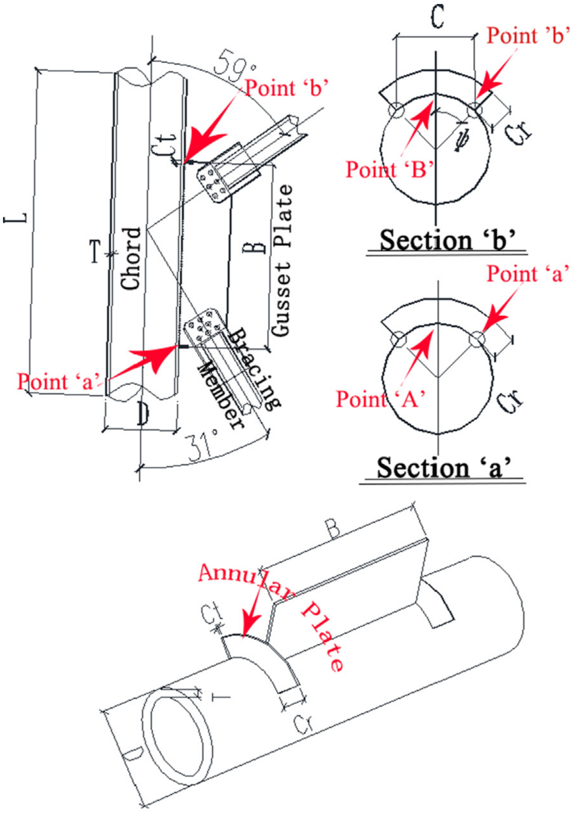


**Fig. 2.** Tube-gusset joint configuration.

determined the major parameters influencing the ultimate strength. Moreover, Packer et al. [11], Lesani et al. [12], Ju and Wang [13], Lv et al. [14], Rong et al. [15], Qian et al. [16], Gho and Yang [17], and Lee and Gazzola [18] performed a series of experimental and analytical investigations on the mechanical behaviour of tubular joints, and developed different formulae for determining the ultimate strength of the tubular joints.

Furthermore, for transmission lines to transmit higher voltages, the towers need to be taller. Low-strength steel cannot be used in the construction of tall towers; it is necessary to use high-strength steel. As such, in the United States and Japan, high-strength steels with yield strengths greater than 690 MPa have been developed, namely HPS690W and BHS700W [19]. In recent years, experimental and numerical studies have been conducted to investigate the ultimate capacity of high-strength hollow steel sections (yield strength ⩾ 460 MPa) [20–27]. However, such studies on the buckling capacity of high-strength steel tubes (Q690) with a circular section are very limited, as are those on tube-gusset joints.

Based on the preceding literature review, it is apparent that the majority of the research has focused on normal-strength steel tubular joints. Currently, insufficient research is available on tube-gusset joints.

**Table 1**

Formulas for the determination of the ultimate strength of tube-gusset joints.

| Sources | $M_u$ | External annular steel plate |
|---|---|---|
| JSSC[1] | $M_u = 7BT^2\sigma_0$ (1) | No |
| Kim[8] | $M_u = \left[0.34\left(\frac{D}{T}\right)^{0.6} + 0.8\left(\frac{B}{D}\right) + 2.9\right]Bg(n')T^2\sigma_0$ (2) | No |
| AIJ[28] | $M_u = 1.26\left[\left(\frac{D}{2T}\right)^{0.2} + \left(\frac{B}{2D}\right)\left(\frac{D}{2T}\right)^{0.1}\right]BT^2\sigma_0$ (3) | No |
| CISC[11] | $M_u = 5\left[1 + 0.25\left(\frac{B}{D}\right)\right]Bf(n')T^2\sigma_0$ (4) | No |
| JSSC[1] | $M_u = 21\frac{C}{D}BT^2\sigma_0$ (5) | Yes |

Note: D – chord diameter; T – chord thickness; B – gusset plate length; C – projected length of annular plate (as shown in Fig. 2); $\sigma_0$ – material yield strength; $f(n') = 1 + 0.3n' – 0.3n'^2$; $g(n') = \frac{1}{3}n' + \sqrt{1 – \frac{8}{9}n'^2}$.

As indicated in Table 1, limited formulae exist for determining the ultimate strength of tube-gusset joints [1,8,11,28]. The Japanese and Canadian specifications [11,28] use empirical formulae for estimating joint capacities based on limited experimental results, which do not consider the constraint effects of brace members. Saeko [1] proposed a formula-drafted means of calculating the ultimate strength of joints, and while the formula $M_u = 7Bt^2\sigma_0$ is concise, it lacks the dimension parameter diameter D, so is generality not useful. The formula proposed by Kim [8] used a similar method to that of Saeko [1], which can obtain the ultimate strength of joints with relative accuracy, as well as consider the effects of the chord-axial compression ratio as the formula proposed by Canadian Institute of Steel Construction (CISC) [11]. However, Deng and Cheng [29,30] concluded that existing design approaches for the ultimate strength of steel tubular K-joints are too conservative. The formulae were developed based on low-strength steel, and further validation is required to determine whether these are applicable to high-strength steel tubular joints. Thus, this study focuses on the behaviour of steel tubular K-joints using high-strength steel.

This paper presents an experimental and numerical study on the ultimate behaviour of high-strength steel tube-gusset plate connections with external annular steel plates on the chord circumference. Firstly, based on a preliminary numerical investigation, static experiments were carried out on full-scale high-strength steel tubular K-joints, with five representative response parameters: (1) chord compression ratio, (2) gusset plate length, (3) chord diameter, (4) chord wall thickness and (5) existence of the external annular steel plate. The minimum strength was taken as the ultimate strength, the load causing more than 3% deformation to the chord diameter and the maximum load that could be carried by the K-joints. Secondly, finite element (FE) models were constructed to validate the behaviour of the K-joint specimens and further investigate the failure mode of the K-joints. Finally, according to the energy theory of steel tubes [31], and based on the experimental and numerical results, a formula is proposed for predicting the ultimate flexural capacity of K-joints with external annular plates.