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Experimental study and theoretical analysis on the ultimate strength of high-strength-steel tubular K-Joints

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ABSTRACT

In order to investigate the failure mode and mechanism of K-joints fabricated using high-strength steel and to develop a formula that can predict their ultimate strength, full-scale tubular K-joints with tube-gusset plate connections of Q690 high-strength steel are fabricated and tested under static loads. Based on the tubular energy theory and virtual work principle and using the ring-generator separation model, a formula for predicting the ultimate strength of high-strength steel K-joints is developed. In order to verify the correctness of the formula, using the finite element model, a sensitivity analysis is performed on the factors that affect the ultimate strength of the joints. The results indicate that the stress in the main post and the thickness and diameter of the main post significantly affect the ultimate strength of the K-joints. Moreover, the results predicted by the proposed formula correlate well with the experimental and numerical results. Hence, the proposed formula can be used for practical engineering design.

1. Introduction

Transmission towers can be considered to be flexible owing to their large height and span in the case of ultra-high voltage transmission towers, and thus, their internal forces are controlled by various loads at a certain extend. Compared to the steel angle tower, the steel tubular tower is more commonly applied because of its smaller windward area and larger cross-section gyration radius. Moreover, these tall towers cannot be constructed using low-strength steel—instead, high-strength steel is required, as shown in Fig. 1. In the United States and Japan, the high-strength steels, HPS690W and BHS700W, have been developed and are widely used [1].

At present, the tube-gusset joint type is applied mainly owing to the convenience of construction it provides, as shown in Fig. 2. However, few scholars have conducted research on the tube-gusset joint, which resists complicated forces, and there exist some irrationalities in the theory at present. Saeko [2] developed a formula that provides a conservative estimation of the ultimate strength of K, TY, and X joints based on experimental data. Kurobane [3] and Werdenier [4] developed a formula for calculating the ultimate strength of TP and XP joints. Soh [5] performed a simple theoretical analysis using a yield line model to determine the ultimate strength of tube-gusset plate joints. Dexter and Lee [6,7] investigated overlapping K-joints and developed a formula for the ultimate strength of this type of joint. Kim [8] performed tests for K-type tube-gusset plate joints and developed a formula for calculating the axial brace forces and ultimate moment acting on the joints. Feng and Young [9] performed tests for T and X cold-formed stainless steel tubular joints, and the developed formulas were found to be more accurate and reliable than the current design strengths calculated using the Australian/New Zealand Standard for stainless steel structures, the International Committee for Research and Technical Support for Hollow Section Structures (CIDECT) design rules, and Eurocode design rules for carbon steel tubular structures. Wang [10] experimentally and numerically investigated the behaviour of tube-gusset K-joint and found the major parameters that influenced the ultimate strength. By combining his results with those in Canada (Packer et al. [11]) and Japan (AIJ-SRC. [12]), he developed formulas for determining the bending capacity of tube-gusset K-joints. Moreover, Lesani et al. [13], Ju and Wang [14], Lv et al. [15], Rong et al. [16], and Gho and Yang [17] performed a series of experimental and analytical investigations on the mechanical behaviour of tubular joints, and developed various formulas for determining the ultimate strength of tubular joints. Qian et al. [18] developed a novel nonlinear formulation for circular hollow-section X- and K-joints, which could accurately predict the failure mechanisms in 2D and 3D frames.

Based on the preceding literature review, it is apparent that the

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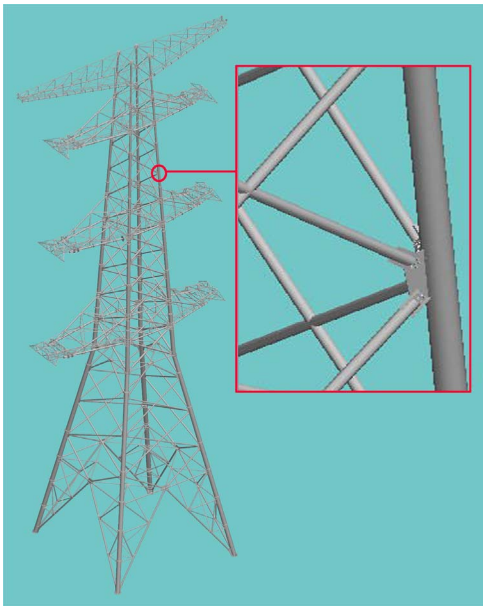


Fig. 1. 3D model of steel tubular tower.

majority of the research has been conducted on tubular joints, and there is insufficient research on the tube-gusset joint. Kim [8] developed a formula for determining the ultimate strength of the K-joints by performing numerical fitting to the experimental data, but this formula is not supported by a theoretical analysis. In contrast, Bao [19] 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; however, the analysis is only applicable to small deformation theory and ignores the effect of the axial force [19]. Deng Hongzhou et al. [20,21] found that the existing design approaches for determining the ultimate strength of steel tubular K-joints are too conservative and that further research is necessary.

In this study, a static test on full-scale high-strength steel tubular K-joints is conducted to investigate the ultimate strength, failure mode, and mechanism of the material. Finite element models are then built to validate the behaviour of the K-joint specimens. According to the energy theory of steel tubes [22] and based on the experimental and numerical results, a formula for predicting the ultimate strength of K-joints is proposed.

2. Current design practice

K-type joints generally comprise bracing members, a main post, and a gusset plate, as shown in Fig. 3. The gusset plate is welded onto the tube wall of the main post, and the bracing members are connected to the gusset plate using bolts. Table 1 shows four design formulas from the existing guides that can be used to determine the ultimate strength of K-type joints [2,8,11,12], and the method for the determination of the ultimate strength is not accurate [20,21] owing to the lack of research on the tube-gusset joint.

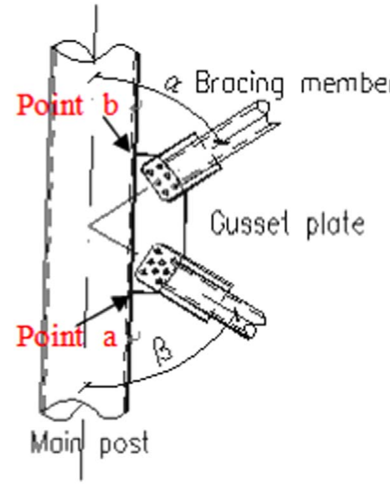


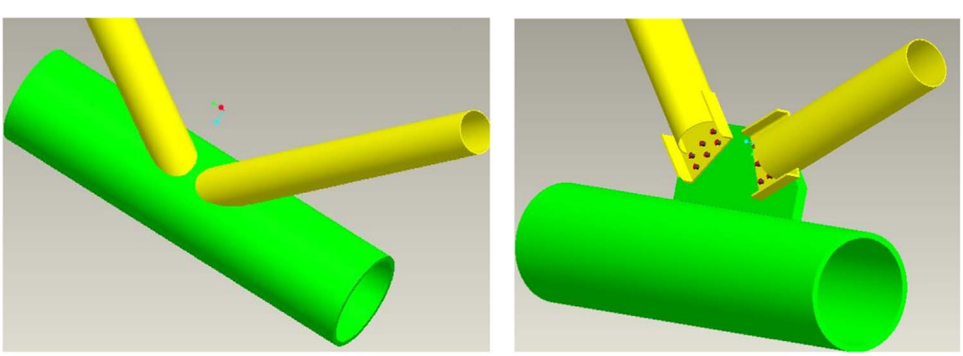
Fig. 3. Configuration of tube-gusset joint.

Table 1
Formulas for determination of ultimate strength of tube-gusset joints.

Sources	Formulas	
JSSC [2]	$M_u = 7Bt^2\sigma_0$	(1)
Kim [8]	$M_u = \left[0.34\left(\frac{D}{t}\right)^{0.6} + 0.8\left(\frac{B}{D}\right) + 2.9\right]\left(\frac{1}{3}n' + \sqrt{1 - \frac{8}{9}n'^2}\right)Bt^2\sigma_0$	(2)
AIJ [1-2]	$M_u = 1.26\left[\left(\frac{D}{2t}\right)^{0.2} + \left(\frac{B}{2D}\right)\left(\frac{D}{2t}\right)^{0.1}\right]Bt^2\sigma_0$	(3)
CISC [2-3]	$M_u = 5\left[1 + 0.25\left(\frac{B}{D}\right)\right](1 + 0.3n' - 0.3n'^2)Bt^2\sigma_0$	(4)

Note: σ_0 is yield strength of material.

Saeko [2] developed the following empirical formula for the determination of the ultimate strength of the joints: $M_u = 7Bt^2\sigma_0$. Eq. (1) is concise, but it has no dimension parameter to account for the diameter *D of the main post*. Therefore, Eq. (1) cannot be used for general applications as diameter D is an important parameter for the determination of the ultimate strength of joints [8,20,21]. Kim [8] also developed a formula that is similar to Eq. (1), which takes into account the effect



(a) Tubular joint (b) Tube-gusset joint

Fig. 2. Types of tube joint.