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Static strength of stainless steel K- and N-joints at elevated temperatures

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ABSTRACT

This paper aims to investigate the static strength of stainless steel gap and overlapped K- and N-joints at elevated temperatures. A numerical parametric study was conducted on circular hollow section (CHS) K- and N-joints under axial loads in the braces at different temperatures ranging from 22 to 760 °C. A wide range of geometric parameters and chord preload ratios of CHS K- and N-joints using duplex, high strength austenitic and normal strength (AISI 304) stainless steel was investigated. The joint strength reduction was compared with reduction factors of yield stress and elastic modulus of stainless steel materials at elevated temperatures. A unified strength equation for CHS K- and N-joints at elevated temperatures was proposed by adopting the reduction factor of yield stress. The statistical analysis shows that the proposed strength equation is accurate for stainless steel K- and N-joints at elevated temperatures.

1. Introduction

Stainless steel tubular structures are increasingly popular due to their aesthetic appearance, improved resistance to fire and corrosion, and superior mechanical performance. Tubular joints are critical components in tubular structures because of their geometric discontinuity and high stress concentration at the connections. The structural behaviours and design of stainless steel tubular joints at ambient temperature have been investigated in recent years. Rasmussen and Young [1] and Rasmussen and Hasham [2] conducted tests on square hollow section (SHS) and circular hollow section (CHS) X- and K-joints using austenitic stainless steel 304L. Feng and Young [3–6] carried out experimental, numerical and theoretical investigations on rectangular hollow section (RHS) T- and X-joints using normal strength stainless steel (AISI 304) and high strength stainless steel (duplex and high strength austenitic). Huang and Young [7,8] conducted experimental tests on ferritic stainless steel RHS T- and X-joints. However, mechanical properties of stainless steel materials in tubular structures experience significant deterioration in fire. The tubular joints are crucial for structural integrity. Therefore, it is important to investigate the structural performance of stainless steel tubular joints at elevated temperatures.

The joint strength at steady elevated temperatures is an important aspect of structural performance of tubular joints in fire. Tan et al. [9] and Shao et al. [10] conducted experimental tests and finite element analysis on carbon steel CHS T-joints under axial compression in the braces. It is found that design equations in EN 1993-1-8 [11], the CIDECT design guide [12] and API RP 2A WSD [13] replacing the steel yield stress at room temperature with that at elevated temperatures may produce unconservative prediction of joint strength at elevated temperatures. However, the strength prediction of the design code and guide [11–13] may be conservative using the reduction factor of steel elastic modulus. Ozyurt et al. [14] carried out numerical study on carbon steel CHS and SHS tubular joints. It is found that the strength reduction of T-, Y- and X-joints under brace axial tension, and K- and N-joints under brace axial loads generally follows the reduction of steel yield stress at elevated temperatures. However, the strength reduction of T-, Y- and X-joints under brace axial compression follows more closely the reduction of steel elastic modulus. Xu et al. [15] developed an artificial neural network model to predict the static strength of carbon steel CHS T-joints under brace axial compression in fire. Fung et al. [16] conducted test and numerical studies on the failure mechanism of CHS T-joints subjected to brace in-plane bending. It is observed that the failure mode of the joints is cracks forming along the weld toes at high temperatures and the effect of temperatures on joint strength reduction is significant. Shao et al. [17] presented a design method for the strength prediction of CHS K-joints at elevated temperatures based on a deforming rate criterion. Shao et al. [18] also numerically investigated the static strength of carbon steel CHS T-joints in fire obtained from steady and transient state analysis. Lan et al. [19] proposed an equation for predicting the joint strength reduction of internally ring-stiffened carbon steel CHS T-, Y- and DT-joints at elevated temperatures. Meanwhile, some studies on the fire resistance of carbon steel tubular

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Table 1
Gap K-joints used for validating FE models.

Specimen	Chord		Brace 1		Brace 2				
	d (mm)	t (mm)	d_1 (mm)	t_1 (mm)	d_2 (mm)	t_2 (mm)	g (mm)	θ_1 (°)	θ_2 (°)
KC48-30 [2]	101.5	2.80	48.0	2.92	48.0	2.92	87	29.2	30.0
KC48-45 [2]	103.0	2.84	48.2	2.92	48.2	2.92	29	44.0	44.5
KC76-30 [2]	101.0	2.79	72.3	2.94	72.3	2.94	24	29.5	30.0
G2C [33]	216.4	7.82	165.0	5.28	165.0	5.28	29.5	60	60

joints under constant loading in fire have also been conducted. Yu et al. [20] conducted tests on carbon steel CHS T-joints after impact loading and found that the T-joints have minor change in fire resistance performance. Chen et al. [21] and Yang et al. [22] carried out experimental and numerical investigations on the failure mechanism of carbon steel CHS and SHS T-joints. It is shown that the T-joints failed by local yielding of chord wall around brace-chord intersection. He et al. [23–25] conducted experimental and numerical studies on carbon steel CHS gap K-joints and proposed a critical temperature method to assess the fire resistance performance of the K-joints. Gao et al. [26,27] experimentally and numerically investigated the fire resistance of carbon steel CHS T-joints without and with reinforcement of collar plates and Y-joints. It is found that the fire resistance of the joints is improved by decreasing the load ratio. Chen et al. [28] conducted experimental and numerical studies on the fire resistance performance of internally ring-stiffened CHS T-joints and found that the internal rings could effectively enhance the fire resistance of the joints.

In contrast to the extensive studies on carbon steel tubular joints in fire, research on stainless steel tubular joints at elevated temperatures remains limited. Feng and Young [29] carried out numerical study on stainless steel RHS and SHS T- and X-joints, and proposed design equations for predicting the joint strength at elevated temperatures by modifying design equations in the CIDECT design guide [30]. Based on the comparison between the joint strength reduction and reduction factors of yield stress and elastic modulus of stainless steel materials, Lan and Huang [31] proposed a unified strength equation for stainless steel RHS, SHS and CHS T- and X-joints at elevated temperatures by introducing a temperature factor. However, there is a lack of research on stainless steel K- and N-joints at elevated temperatures.

This paper focuses on the static strength of stainless steel gap and overlapped CHS K- and N-joints under axial loads in the braces at elevated temperatures. A wide range of geometric parameters and different chord preload ratios of CHS K- and N-joints using duplex, high strength austenitic and normal strength (AISI 304) stainless steel were investigated. Based on the comparison between the joint strength reduction and reduction factors of yield stress (0.2% proof stress) and elastic modulus of stainless steel materials, a unified strength equation for CHS K- and N-joints at elevated temperatures was proposed by adopting the reduction factor of yield stress of stainless steel materials.

2. Finite element model

2.1. General

The finite element (FE) software ABAQUS [32] was used to conduct the numerical analysis. It is noted that tests on steel tubular K- and N-joints at steady elevated temperatures are not available in existing literature. Tan et al. [9] conducted experimental tests on carbon steel CHS T-joints under brace axial compression at steady elevated temperatures. Lan et al. [19] successfully developed FE models which are capable of producing reasonably accurate predictions for the joint strengths in fire. In addition, Lan and Huang [31] also validated FE models of stainless steel X- and T-joints against the experimental and numerical joint strengths at room and elevated temperatures reported by Feng and Young [29]. It is also noted that tests on stainless steel tubular K- and N-joints at room temperature remain limited. Thus, the available test results of gap CHS K-joints using normal strength austenitic stainless steel (AISI 304) [2] and carbon steel [33], and completely overlapped N-joints using carbon steel [34,35] at room temperature were used to validate the finite element models in this study. The joint parameters of the CHS K- and N-joints specimens are shown in Tables 1 and 2, including brace diameter (d_1 and d_2), brace wall thickness (t_1 and t_2) for gap K-joints, through brace diameter (d_1), through brace wall thickness (t_1), lap brace diameter (d_2), lap brace wall thickness (t_2) for overlapped N-joints, chord diameter (d), chord wall thickness (t), and angle between brace and chord members (θ_1 and θ_2). Other joint parameters not listed in Tables 1 and 2 are detailed in Rasmussen and Hasham [2], Kurobane et al. [33], Gho et al. [34] and Fung et al. [35]. The configuration and notations of the specimens are shown in Fig. 1.

2.2. Material properties

The adopted elastic modulus (E_0), yield stress (0.2% proof stress, f_y), ultimate stress (f_u) and ultimate strain at ultimate stress (ε_u) for the specimens [2,33–35] are summarised in Table 3. The values of E_0, f_y and f_u reported by Rasmussen and Hasham [2] are adopted in developing the finite element models of stainless steel specimens KC48-30, KC48-45 and KC76-30. The values of ε_u and the corresponding stress-strain curves for specimens KC48-30, KC48-45 and KC76-30 are not reported in Rasmussen and Hasham [2], and thus they were obtained from the predictive equations for stainless steel materials proposed by Rasmussen [36]. The other three specimens (G2C [33], N-joint [34] and N-joint [35]) are in carbon steel materials. The values of f_y and f_u of specimen G2C are reported by Kurobane et al. [33], and thus adopted in developing the finite element model in this study. However, the values of E_0 and ε_u are not reported [33]. The adopted values of E_0 and ε_u in the FEM of specimen G2C were taken as 210 GPa and 10%, respectively, in accordance with those in Fleischer et al. [37] in which the adopted value of ε_u for S355, S460 and S690 steel is 10%. Only the values of E_0, f_y and f_u are reported in Gho et al. [34], and thus the value of ε_u for N-joint [34] is also taken as 10% in this study. As the stress-strain curve was not reported in Kurobane et al. [33] and Gho et al.

Table 2
Overlapped N-joints used for validating FE models.

Specimen	Chord		Through brace		Lap brace				
	d (mm)	t (mm)	d_1 (mm)	t_1 (mm)	d_2 (mm)	t_2 (mm)	g (mm)	θ_1 (°)	θ_2 (°)
N-joint [34]	219.1	7.9	168.3	7.1	88.9	5.5	143.0	90	30
N-joint [35]	457.2	12.7	273.1	9.3	168.3	7.1	85	90	45