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Structural design of cold-formed stainless steel tubular X- and T-joints at elevated temperatures

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ABSTRACT

This paper presents a numerical parametric study on ultimate strength of cold-formed stainless steel tubular X- and T-joints at elevated temperatures. Extensive numerical simulations were carried out on SHS, RHS and CHS tubular X- and T-joints subjected to brace axial compression at different elevated temperatures ranging from 22 to 760 °C. A wide range of geometric parameters and chord preload ratios was considered. The material properties of duplex, high strength austenitic and normal strength stainless steel (AISI 304) were carefully incorporated in the finite element models. The joint strength reduction was compared with the reduction factors of yield stress and elastic modulus of stainless steel materials at elevated temperatures. A unified equation for predicting ultimate strength of X- and T-joints at elevated temperatures was proposed by introducing a temperature factor. The statistical analysis shows that the proposed strength equation is reliable and accurate.

1. Introduction

The popularity of cold-formed stainless steel tubular joints is increasing owing to their aesthetic appearance, improved fire resistance, superior corrosion resistance and advantageous mechanical performance. Previous researches on cold-formed stainless steel tubular joints are mostly focused on welded joints at room temperature. Tests on normal strength stainless steel tubular X- and K-joints were carried out by Rasmussen and Young [1] for square hollow sections (SHS) and Rasmussen and Hasham [2] for circular hollow sections (CHS). Feng and Young [3,4] performed experimental investigation on normal and high strengths stainless steel tubular T- and X-joints of square and rectangular hollow sections. Feng and Young [5,6] conducted numerical and theoretical analysis on strength of SHS and RHS normal and high strength stainless steel tubular T- and X-joints, and proposed design equations for the T- and X-joints. As the mechanical properties of steel materials deteriorate drastically with increasing temperature, steel tubular joints may fail at a load substantially lower than the failure load at room temperature. The joint failure could result in the collapse of entire steel tubular structures. Therefore, it is significant to investigate ultimate strength of steel tubular joints and to propose reliable design methods for steel tubular joints at elevated temperatures.

Joint strength at steady elevated temperatures and fire resistance of steel tubular joints subjected to constant loading in fire and are two important aspects of performance of steel tubular joints in fire. Tan et al. [7] conducted tests and numerical simulation on structural behavior of CHS tubular T-joints at elevated temperatures. It is found that both joint strength and plastification area on chord decrease as temperature increases. Ultimate strength of SHS and CHS T-, Y-, X-, N- and non-overlapped K-joints at elevated temperatures was numerically investigated by Ozyurt et al. [8]. The results show that the design equations specified in EN 1993-1-8 [9] and CIDECT [10] but replacing the yield stress of steel at room temperature with corresponding values at elevated temperatures could be used to calculate the strength of T-, Y- and X-joints subjected to brace axial tension, and gap K- and N-joints. It is also found that strength reduction of CHS T-, Y- and X-joints subjected to brace axial compression generally follows closely the reduction of steel elastic modulus at elevated temperatures. Shao et al. [11] carried out an experimental study on the performance of CHS tubular T-joints subjected to brace and chord axial compression at elevated temperatures. It is found that design equations specified in EN 1993-1-8 [9], CIDECT [10] and API RP 2A WSD [12] by using the yield stress of steel material at elevated temperatures

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Nomenclature

d	chord diameter
b	chord width
h	chord depth
t	chord wall thickness
l	chord length
θ	in-plane brace angle
β	brace to chord diameter ratio ($=d_1/d$) or brace to chord width ratio ($=b_1/b$)
T	temperature (°C)
f_{y0}	0.2% yield stress at room temperature
n	chord preload ratio
E_0	elastic modulus at room temperature
$k_{y,T}$	stainless steel yield stress reduction factor at temperature T
k_T	temperature factor
N_{20}	joint strength at ambient temperature
R_T	joint strength reduction factor at temperature T ($=N_T/N_{20}$)
r_{si}	strength ratio ($=N_{fi}/N_{ei}$)
d_1	brace diameter
b_1	brace width
h_1	brace depth
t_1	brace wall thickness
l_1	brace length
A_0	cross section area of chord member
2γ	chord diameter to thickness ratio ($=d/t$) or chord width to thickness ratio ($=b/t$)
N	number of joints analyzed in each case
$f_{0.2,T}$	0.2% yield stress at temperature T
β_0	reliability index
E_T	elastic modulus at temperature T
$k_{E,T}$	stainless steel elastic modulus reduction factor at temperature T
COV	coefficient of variation
N_T	joint strength at temperature T
N_{fi}	joint strength obtained from finite element analysis
N_{ei}	joint strength calculated from proposed strength equation

may produce non-conservative joint strength prediction at elevated temperatures. However, by using reduction factor of steel elastic modulus, the design equations in the above three design guidelines [9,10,12] could provide conservative estimation for joint strength. Nguyen et al. [13–16] carried out experimental and numerical investigations on the fire resistance of CHS tubular T-joints subjected to brace axial compression and in-plane bending. The results show that effect of brace to chord diameter ratio on fire performance of tubular T-joints is significant. Yu et al. [17] focused on the performance of impacted CHS tubular T-joints and found that the critical temperature of the impacted joint is higher than that without impact loading. Chen et al. [18] conducted test and finite element studies on the failure modes and fire resistance of CHS tubular T-joints. The results show that the failure mode is characterized as plastic failure of chord face around brace-chord intersection and joint failure occurs when the temperature exceeds a critical value. He et al. [19] presented test and numerical investigations on critical temperature of CHS gap tubular K-joints and found that the critical temperature of the K-joints decreased rapidly with increasing brace loading ratio and initial chord stress. Afterwards, He et al. [20] proposed a critical temperature method for evaluating the fire resistance of the K-joints. Yang et al. [21] experimentally studied the fire resistance of SHS tubular T-joints and found that the failure mode is local buckling on chord wall near chord-brace intersection.

The aforementioned studies on performance of steel tubular joints in fire have been focused on carbon steel tubular joints. However, research on cold-formed stainless steel tubular joints at elevated temperatures is limited. Feng and Young [22] conducted numerical investigation on ultimate strength of SHS and RHS cold-formed stainless steel tubular T-joints, X-joints and X-joints with chord preload at elevated temperatures. Design equations, obtained from modifying the design equations for carbon steel tubular joints given in CIDECT [10] by introducing a temperature factor, were proposed for predicting ultimate strength of the T- and X-joints at elevated temperatures. It is noted that the failure load-to-nominal strength ratio ranges from 0.53 to 1.71 and COVs of the strength ratio calculated from the design equations proposed by Feng and Young [22] are relatively high. These indicate that the proposed design equations may produce scattered and inaccurate joint strength predictions. Furthermore, design equations for predicting ultimate strength of CHS stainless steel tubular joints at elevated temperatures are currently not available. Therefore, there is a need to propose reliable and accurate strength equations for SHS, RHS and CHS stainless steel tubular joints at elevated temperatures.

A numerical parametric study on ultimate strength of cold-formed stainless steel tubular X- and T-joints of square hollow section (SHS), rectangular hollow section (RHS) and circular hollow section (CHS) subjected to brace axial compression at elevated temperatures was presented in this paper. A wide range of geometric parameters and chord preload ratios are investigated. Based on the comparison between the stainless steel tubular joint strength reduction and the reduction factors of yield stress (0.2% proof stress) and elastic modulus of stainless steel materials, a unified strength equation for the X- and T-joints at elevated temperatures was proposed by introducing a temperature factor.

2. Finite element model

A finite element model (FEM) has been developed to conduct numerical analysis. This section describes the finite element modeling and validation. Finite element analysis (FEA) program ABAQUS was used in this study. Test results of T-joint, X-joint and X-joints with chord preload at room temperature [3,4] and finite element results of T-joint, X-joint and X-joints with chord preload at elevated temperatures [22] were used for validation. Duplex, high strength austenitic and normal strength stainless steel (AISI 304) tubular joints were used for the finite element analysis. Table 1 shows the parameters of the T-joint, X-joint and X-joints with chord preload, namely chord depth (h), chord width (b), chord wall thickness (t), brace depth (h_1), brace width (b_1), brace wall thickness (t_1), chord preload ratio (n) and joint temperature (T). The chord preload ratio (n) equals to compressive chord preload (N_p) to chord yield load ($A_0 f_{0.2,T}$) ratio. Other joint parameters not listed in Table 1 are detailed in Feng and Young [3,4,22] for cold-formed stainless steel tubular T- and X-joints. It should be noted that for SHS, RHS tubular joints failed at chord side wall and CHS tubular joints, the ultimate strength of tubular joints is determined by the peak load or deformation limit (3%b or 3%d) in load–displacement curves. If the deformation at the peak load is smaller than the deformation limit, the peak load is considered to be the joint strength. If the deformation at the peak load is larger