Engineering Structures 59 (2014) 574–586

Contents lists available at ScienceDirect

Engineering Structures

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

Elevated temperature resistance of welded tubular joints under axial load in the brace member

E. Ozyurt [a], Y.C. Wang [a,*], K.H. Tan [b]

[a] School of Mechanical, Aerospace and Civil Engineering, University of Manchester, UK
[b] Department of Civil and Environmental Engineering, Nanyang Technological University, Singapore

ARTICLE INFO

Article history:
Received 9 August 2013
Revised 7 November 2013
Accepted 11 November 2013
Available online 21 December 2013

Keywords:
Circular hollow section (CHS)
Square hollow section (SHS)
T-joints
K-joints
X-joints
Y-joints
N-joints
Finite element model
Ultimate capacity
Elevated temperatures

ABSTRACT

This paper presents the results of a study to obtain the ultimate capacity of welded steel tubular joints at elevated temperatures. Finite Element (FE) simulations of welded tubular joints with axially loaded brace member made of CHS or SHS at different elevated temperatures were carried out using the commercial Finite Element software ABAQUS v6.10-1 [1]. After validation, extensive numerical simulations were conducted on T-, Y-, X-, N- and non-overlapped K-joints subjected to brace axial compression or tension, considering a wide range of geometrical parameters. The material and geometrical nonlinearities, which have significant influence on the ultimate strength of tubular joints at elevated temperatures, were taken into account. Uniform temperature distribution was assumed for both the chord and brace members.

Results of the numerical simulation were compared with calculation results using the design equations in Eurocode EN 1993-1-2 [3] and CIDECT design guide [16] but replacing the yield stress of steel at ambient temperature by those at elevated temperatures. It is found that for gap K- and N-joints and for T-, Y- and X-joints with the brace member under axial tensile load, this approach is suitable. However, for CHS T-, Y- and X-joints under brace compression load, this method overestimates the ultimate load carrying capacity of the joint. In fact, for these situations, the joint strength reduction at increasing temperatures follows more closely the reduction in the elastic modulus of steel at elevated temperatures.

1. Introduction

The popularity of hollow structural sections of all types has increased in the recent decades owing to their attractive appearance, light weight and structural advantages. They have been widely used in onshore and offshore structures e.g. bridges, towers, space-trusses, lattice girders, space-frame roof systems, offshore platforms, etc. For these structures, fire presents one of the most severe design conditions, because the mechanical properties of the steel degrade as the temperature increases. It is important that the behaviour of the tubular structures at high temperatures is thoroughly understood and reliable methods are available to calculate their strengths.

This paper investigates the behaviour of welded tubular structural joints at elevated temperatures. The ambient temperature behaviour of welded tubular joints has been subject to extensive research studies [17–21]. However, there is a paucity of research of their behaviour at elevated temperatures. Nguyen et al. [12,13] carried out both experimental and numerical analysis on the behaviour of welded tubular joints at elevated temperatures. In this research, they conducted five full scale circular hollow section (CHS) T-joints subjected to axial compression in the brace member at different temperatures. The results show that design guide predictions overestimated the ultimate load carrying capacity of axially loaded CHS T-joints at elevated temperatures. Cheng et al. [5] carried out some experimental tests and parametric simulations of CHS T-joints at elevated temperatures with the brace member in compression. They observed that the critical mode of joint failure was plastification of the chord face. They performed a number of numerical simulations to investigate the effects of different design parameters. However, they did not give any guidance on joint strength design calculation. He et al. [7] tested two tubular gap K-joints in order to investigate joint temperature development and structural behaviour under heating. They made a comparison between the joint failure loads from their tests and from their calculations using EN 1993-1-8 [4] with the elevated temperature steel strength. This comparison showed that the EN 1993-1-8 calculation result was safe in one case (test result higher than the calculation result by 17%) and unsafe (−7%) in the other case. However, a detailed examination of their definition of the joint failure temperature, based on an arbitrary rate of displacement, may be too conservative. Meng et al. [11] and Liu et al. [9] present some experimental and numerical research results of the structural behaviour of steel planar tubular trusses subjected to fire, although these publications do not address the issue of joint behaviour.

* Corresponding author.
E-mail address: yong.wang@manchester.ac.uk (Y.C. Wang).

0141-0296/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.engstruct.2013.11.014

Nomenclature

CHS	circular hollow sections	L	length of chord
SHS	square hollow sections	l	length of brace
D	diameter of chord	P_{20}	ultimate joint strength at ambient temperatures
d	diameter of brace	P_θ	ultimate joint strength at elevated temperatures
T	wall thickness of chord	β	ratio of brace diameter to chord diameter (=d/D)
t	wall thickness of brace	γ	ratio of chord diameter to twice chord thickness (=$D/2T$)
g	gap length between weld toes of braces	θ	brace-to-chord intersection angle

Currently, there is no design method to calculate the ultimate strength capacity of these joints at elevated temperatures. It may be possible to use the equations for ambient temperature design in design codes such as Eurocode EN 1993-1-8 [4] or design guide such as CIDECT guide No. 1 [16] and by replacing the yield stress of steel at ambient temperature by that at the elevated temperature. However, this approach may not be appropriate. These equations have been derived based on small deflections in the chord face. At elevated temperatures, as observed by Nguyen et al. [12], the chord face may undergo large distortions and their effects should be considered.

The purpose of this paper is to investigate the ultimate capacity of welded steel tubular joints at elevated temperatures, based on the results of finite element (FE) simulations of CHS or SHS tubular joints with axially loaded brace member at different elevated temperatures using the commercial Finite Element software ABAQUS v6.10-1. After validating the simulation model, extensive numerical simulations were conducted on T-, Y-, X-, N- and non-overlapped K-joints subjected to brace axial compression or tension, considering a wide range of geometrical parameters. The computed results were used to check whether it is appropriate to only modify the yield stress of steel for temperature effect for different joint types, geometric parameters and loading conditions.

2. Validation of finite element model

The general finite element package ABAQUS/Standard v6.10-1 [1] was used. For validation, the experimental results of Nguyen et al. [12] on tubular T-joints (Fig. 1a) at 20 °C, 550 °C and 700 °C, which appear to be the only ones to have been carried out for welded tubular joints at elevated temperatures, and the test results of Kurobane et al. [8] on K-joints (G2C-joint, Fig. 1b) at ambient temperature, were used. Owing to symmetry in loading and geometry, to reduce computational time, only a quarter of the T-joints and one half of the K-joints were modelled, with the boundary conditions for symmetry being applied to the nodes in the various planes of symmetry.

Table 1 summarises the geometric parameters of the T- and K-joints. The dimensionless parameter, β is the ratio of the brace diameter to the chord diameter (=d/D); and θ is the angle between the brace and chord members.

The elevated temperature tests of Nguyen et al. [12] were carried out under steady state in which the temperature of the structure was raised to the required level and the mechanical load was then applied. Because of this, the Riks method was chosen to simulate the large deformation behaviour.

2.1. Material properties

For the tubular T-joints tested by Nguyen et al. [12], the steel grade was S355 with a yield strength f_y = 380.3 N/mm^2 and an ultimate strength f_u = 519.1 N/mm^2 from the coupon tests at ambient temperature. The elastic modulus of steel was assumed to be 210 GPa. The elevated temperature stress–strain curves were based on Eurocode EN-1993-1-2 [3]. In the ABAQUS simulation model, the true stress–strain curve was input after converting the engineering stress–strain curve into the true stress and logarithmic strain curve by using the following equations [2]:

$$\varepsilon_T = \ln(1+\varepsilon) \quad (1)$$

$$\sigma_T = \sigma(1+\varepsilon) \quad (2)$$

where ε_T is the true strain, ε the engineering strain, σ_T the true stress and σ is the engineering stress.

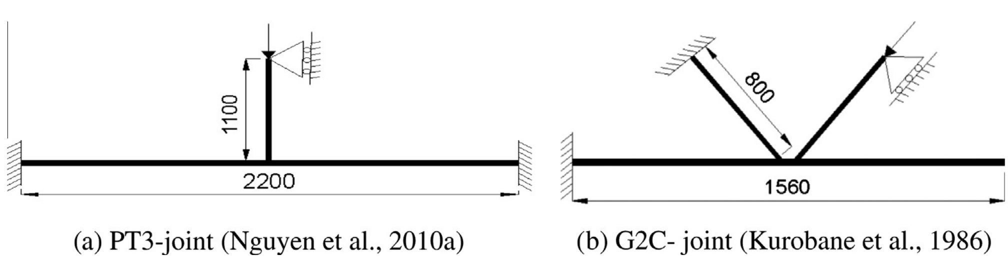

Fig. 1. Tested joints used for validation.

Table 1
Joint test specimens used for FE model validation.

Joint name	D (mm)	d (mm)	T (mm)	t (mm)	g (mm)	β (d/D)	θ (°)
PT3 (Nguyen et al. [12])	244.5 (L = 2200)	168.3 (l = 1100)	6.3	6.3	–	0.69	90
G2C [8]	216.4 (L = 1560)	165.0 (l = 800)	7.82	5.28	29.5	0.76	60