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Parametric study on structural behavior of tubular K-joints under axial loading at fire-induced elevated temperatures

Neda Azari Dodaran, Hamid Ahmadi*, Mohammad Ali Lotfollahi-Yaghin

Faculty of Civil Engineering, University of Tabriz, Tabriz 5166616471, Iran

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ABSTRACT

Present research used the results of 405 finite element (FE) analyses to study the effect of the joint geometry on the ultimate strength and initial stiffness of tubular K-joints subjected to axial loading at fire-induced elevated temperatures. The FE models were validated against the data available from experimental tests. Structural behavior under different temperatures (200 °C, 400 °C, 500 °C, and 700 °C) was investigated and compared to the behavior at ambient temperature (20 °C). Results showed that by increasing the temperature, the ultimate strength and initial stiffness may decrease drastically. On average, the reduction of ultimate strength is 5%, 19%, 51%, and 83% at 200 °C, 400 °C, 550 °C, and 700 °C, respectively. A parametric study was conducted to investigate the effect of dimensionless geometrical parameters (β, γ, θ, and τ) on the ultimate strength and initial stiffness. Afterwards, ultimate strength data extracted from the FE analyses was compared with the values calculated from the equations proposed by available design codes in which the ultimate strength of the joint at elevated temperatures is obtained by replacing the yield stress of the steel at ambient temperature with the corresponding value at elevated temperature. It was indicated that this method may not have acceptable accuracy for carbon steel K-joints under axial loading. Hence, a new design formula was developed, through nonlinear regression analyses, to determine the ultimate strength of K-joints subjected to balanced axial loads at elevated temperatures.

1. Introduction

Tubular structures are widely used in space structures such as stadiums, airport terminals and offshore jacket platforms (Fig. 1a). The main advantages of such tubular structures are their high strength-to-weight ratio, attractive appearance, low drag coefficient, easy fabrication, etc. Offshore structures may be exposed to the fire during their construction and service life.

The intersection among the chord and brace members in which the prepared ends of the braces are welded to the undisturbed surface of the chord is called a tubular joint (Fig. 1b). Tubular joints require more attention compared to the other components of the structure to ensure structural integrity. The reason is that the joint may fail before the main member. Moreover, tubular joints are among the most critical parts of a jacket structure; because of the complex failure mechanism and the presence of high stress concentration, residual stresses, geometric discontinuity, and possible construction defects. Furthermore, since the radial stiffness of the chord is lower than the axial stiffness of the brace, a tubular joint often fails on the chord surface in the vicinity of the brace-to-chord intersection. Since the mechanical characteristics of steel material degrade considerably at elevated temperature, a tubular joint may fail subjected to a load far below its static strength at ambient temperature. Consequently, the entire structure might collapse after the failure of one or several tubular joints. Therefore, it is important to study the performance of tubular joints at the fire condition.

Majority of research works on tubular structures at elevated temperatures have focused on relatively simple joints such as T-joints, while the joints with more complex geometry such as K-joints have not been investigated thoroughly. However, comparing to simple tubular joints, K-joints are more commonly used in the construction of offshore structures because two brace members in a K-joint are mainly subjected to balanced axial loads which can significantly reduce the stress concentration around the brace-to-chord intersection. It should be noted that different joint types may have different failure mechanism and performance at elevated temperature. As far as the authors are aware, no design equation is available to determine the ultimate capacity of tubular carbon steel K-joints at elevated temperatures under axial load. Hence, further research is needed to provide detailed guidelines on static assessment of tubular K-joints at elevated temperature.

In the present paper, results of a parametric study conducted on the

* Corresponding author.
E-mail address: h-ahmadi@tabrizu.ac.ir (H. Ahmadi).

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Nomenclature

A	Brace area
d	Brace diameter
D	Chord diameter
E_a	Young's modulus at 20 °C
E_{aT}	Young's modulus at elevated temperature
f_{y0}	Yield stress at 20 °C
f_{yT}	Yield stress at elevated temperature
F_u	Ultimate strength
g	Gap size
k_{ET}	Ratio of Young's modulus at elevated temperature to the Young's modulus at 20 °C
k_g	Joint geometry factor
k_p	Chord stress factor of Eurocode equation [26]
k_{pT}	Ratio of the proportional limit at elevated temperature to the yield stress at 20 °C
k_{yT}	Ratio of effective yield stress at elevated temperature to the yield stress at 20 °C
l	Brace length
L	Chord length
t	Brace thickness
T	Chord thickness
R^2	Coefficient of determination
Q_f	Chord stress factor of CIDECT [22] equation
α	Chord length parameter ($2L/D$)
β	Brace-to-chord diameter ratio (d/D)
γ	Chord radius-to-wall thickness ratio ($D/2T$)
τ	Brace-to-chord wall thickness ratio (t/T)
ζ	Gap size-to-chord diameter ratio (g/D)
θ	Brace inclination angle
λ	Ratio of ultimate strength at elevated temperature to ultimate strength at 20 °C
ε	Engineering strain
ε_T	True strain
σ	Engineering stress
σ_T	True stress

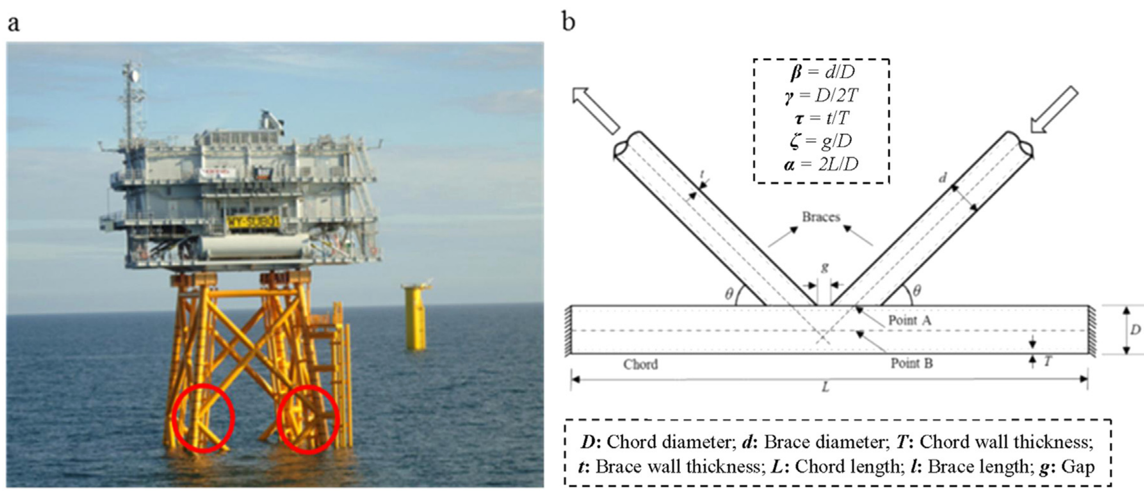

Fig. 1. (a) Tubular K-joints in a jacket offshore platform and (b) geometry and boundary conditions of a tubular K-joint subjected to balanced axial loads.

static strength and initial stiffness of tubular K- joints under axial loads are presented. A total of 405 FE analyses were conducted by ANSYS in order to study the effect of temperature and the dimensionless geometrical parameters of the K-joint on its static strength and initial stiffness. Dimensionless geometrical parameters (β, γ, τ, θ, and ζ), used to readily relate the behavior of a tubular joint to its geometrical properties, are defined in Fig. 1b. Developed FE model was validated against available experimental data reported by Tan et al. [1], Fung et al. [2], Gho et al. [3], and Kurobane et al. [4]. Based on the results of FE models, a comprehensive ultimate strength database was prepared and finally through nonlinear regression analysis, a parametric equation was established to evaluate the ultimate strength of K-joints at elevated temperature under axial loading.

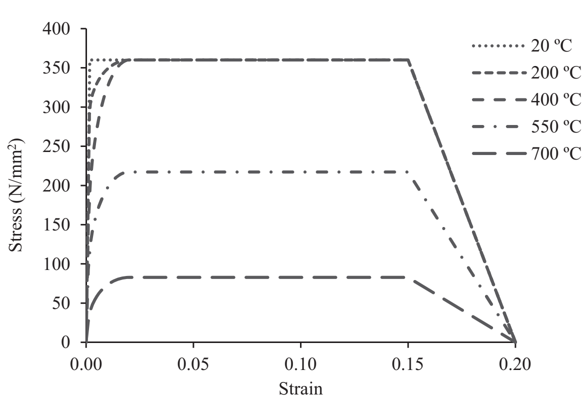

Fig. 2. Stress and strain relationships at elevated temperatures.

2. Literature review

Two following paragraphs review the research works conducted on the static strength of tubular joints at ambient and elevated temperatures, respectively.

Choo et al. [5] investigated the static strength of doubler plate reinforced X-joints under in-plane loading. Van der Vegte et al. [6] studied the ultimate strength of T-joints reinforced with doubler plates subjected to brace compression. Yang et al. [7] investigated the static strength of tubular Y-joints under brace compressive load. Nassiraei et al. [8–10] studied the effect of joint geometry and collar plate size on the ultimate strength and failure modes of T/Y-joints reinforced with collar plates under axially compressive, tensile, and in-plane bending loads. Zhu et al. [11] carried out experimental tests to investigate the static strength of CHS T-joints reinforced with external stiffening rings. Nassiraei et al. [12–14] studied the initial stiffness, ultimate strength, and failure modes of doubler plate reinforced T/Y-joints. They also