EXPERIMENTAL STUDY ON TUBULAR STEEL T-JOINTS UNDER FIRE CONDITIONS

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The study focuses on the behavior of square hollow section (SHS) T-joints under fire conditions. To analyze the fire resistance and failure modes of the joints, three full-scale SHS joints specimens with different geometries were tested under standard ISO-834 fire conditions. The specimens were set to sustain the load resulted in compression of the brace of the joint during the heating stage. The temperature of the specimens was measured with the thermocouples on the surface of the tubes and the deformations were measured at the brace/chord intersection until the failure of the specimen. The experimental results prove that the occurring failure mechanism of the joint depends on its geometrical properties. For the specimens with a smaller brace the failure was plastification of the top chord; for the second specimen the main failure was plastification of the sidewalls of the chord and for the third specimens two failure modeswere observed – local buckling of the chord sidewalls and brace sidewalls. The geometry influences also the temperature distribution of the specimen. The temperature development of the smaller brace joint can be considered uniform, while the temperatures of the joints with the bigger brace the temperature differ noticeably.

Keywords: Tubular section,T-joint, axial load, failure mode, elevated temperatures, experimental test.

1 Introduction

Hollow sections are widely used in many types of structures. Connections, as the components of steel truss transferring internal forces, require a careful attention, especially at elevated temperatures. It was reported, that the increasing temperature could significantly change the moment-rotation capacity of the joint, which cause deformation and may lead to the loss of the integrity of the whole structure. However, the research work mostly concerned the conventional components or structures such as steel beams, columns, frames at ambient temperature. Thus, the data available on the behavior of hollow section joints under fire conditions are scarce due to high laboratory costs and very specialized equipment needed for the experiments.

The experimental research data on the square hollow section joints scares. The available data are presented by Yang et al. (2013). The research was conducted on two full-scale SHS T-joints tests. The specimens were axially loaded, exposed to standard fire ISO-834. The aim of the research was to determine the fire resistance and the failure mechanism of the joint. Tubular T-joints were also investigated by Nguyen et al. (2010, 2012a, 2012b), Tan et al. (2013) and Fung et al. (2016), however, the scope of their interest was on the circular hollow sections (CHS). The research considered the mechanical behavior of the joints subjected to axial loading or in-planebending of the brace of the joint under fire conditions. During the experimental and

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numerical studies, it was found that the high temperature surrounding the specimens might change the failure mode of the joint at the ambient temperature, especially when the bending moment is applied. The high temperature also reduces the ultimate strength of the joint.

It can be seen from the abovementioned studies, that the technical data available on SHS T-joints is limited and more research concerning the topic is on high demand. The more accurate data could improve the fire design approach of welded tubular joints. Therefore, this paper presents the experimental tests results on full-scale axially loaded square tubular T-joints at elevated temperatures carried out by Tampere University. The aim is to investigate the behavior, fire resistance and failure characteristics of square hollow section T-joints at elevated temperatures under axial compression of the brace.

2 Test experiment

The experimental study included three square hollow section T-joints with different geometrical parameters.All tubes were fabricated from cold-formed double grade S355/420 steel sections. In Table 1 the dimensions of the cross-sections of the specimens are summarized and illustrated in Figure 1. No fire protection was applied on the steel elements.

Table 1. Geometric properties and loading of the specimens.

Specimen	Chord (mm)		Brace (mm)	
	Width	Thickness	Width	Thickness
S1	200	5	100	5
S2	200	5	180	5
S3	200	8	180	5

2.1 Test rig and procedure

The tests were carried out in the rectangular gas furnace with internal dimensions 3000 mm x 3000 mm x 4000 (height x width x length). The brace of the joint was fixed to the loading frame at the roof of the furnace. Two hydraulic loading jacks fixed to the loading frame applied the loading to the specimens. Figure 1 presents the joint specimen and Figure 2 the test rig with installed loading frame and the specimen in the furnace. During the test, the displacement of the brace and ends of the chord was measured by LVDTs at the ends of the chord members, as a displacement of the hydraulic loading jacks and temperature of the specimens by thermocouples located in various locations of the joints and in the furnace. The installed thermocouples in the specimen are presented in Figure 1and thelocation of the hydraulic loading jacks is presented in Figure 2.

The experimental tests were divided into two phases. In the first stage, the specimens were loaded with prescribed axial load resulting in compression force in the brace of the joint. The desired load was applied by the hydraulic loading jacks at the ends of the chord. In the second stage, the loaded specimens were heated up according to standard fire ISO-834 curve. The heating of the specimens continued until the failure of the specimen was reached.

The load of the joints was defined as a ratio of the axial load capacity of the joint at the ambient condition, which was calculated according to EN 1993-1-8 (2005). The equations used for the calculations of the design joints resistance are described as Eq. (1-3). The equations are applied in regard to the type of the failure mode of the joint characterized by β parameter.βparameter is defined as the ratio of the width of the chord to the width of the brace. Eq. (1) provides the equation to calculate the design strength of the joint, which failure mode is a chord face failure with $\beta \leq 0.85$; Eq. (2) to calculate the design strength of the joint, which failure mode is chord sidewall buckling with$\beta = 1.0$; and Eq. (3) to calculate the design strength of the joint, which failure mode is brace failure with $\beta \geq 0.85$.

All symbols are explained and described in EN 1993-1-8 (2005). The final values of the design resistance of the joints $N_{1,Rd}$ and the applied load during the tests are summarized in Table 2.

Chord face failure $\beta \leq 0.85$

$$N_{1,Rd} = \frac{k_n f_{y0} {t_0}^2}{(1-\beta) sin\theta_1}\left(\frac{2\eta}{sin\theta_1} + 4\sqrt{1-\beta}\right)/\gamma_{M5} \tag{1}$$

Chord sidewall buckling $\beta = 1.0$

$$N_{1,Rd} = \frac{k_n f_b t_0}{sin\theta_1}\left(\frac{2h_1}{sin\theta_1} + 10t_0\right)/\gamma_{M5} \tag{2}$$

Brace failure $\beta \geq 0.85$

$$N_{1,Rd} = f_{yi} t_1 \left(2h_1 - 4t_1 + 2b_{eff}\right)/\gamma_{M5} \tag{3}$$

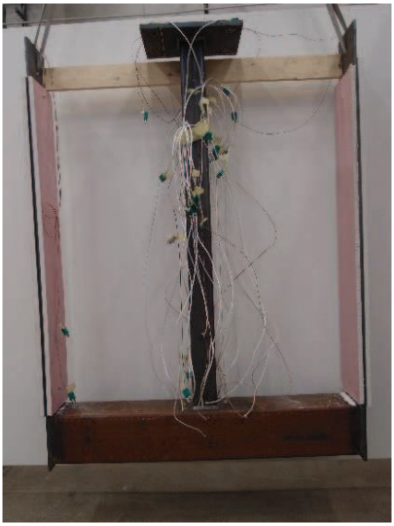

Figure 1. Joint specimen

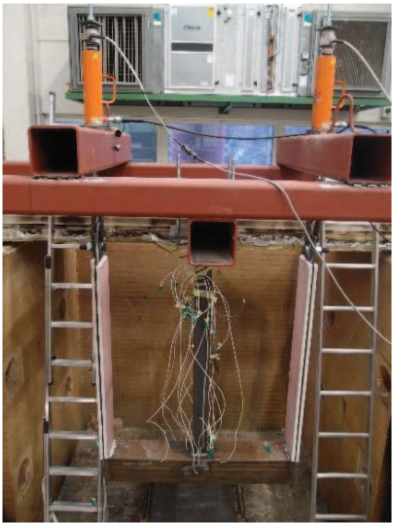

Figure 2. Test set up with joint specimen and loading frame

3 Failure modes of the specimens

The most important part of the research was to observe what type of failure mechanism would lead to permanent damageof the specimens. The tests were carried until the failure of the joint. For the specimen *S1* the occurred failure mode was local plastification of the top chord wall. The specimen *S2*failed by local buckling of the chord sidewall, however, significant local buckling of the top chord face was also observed. Specimen *S3* characterized with thick chord wall, therefore the failure mechanisms occurred in the joint were local buckling of the brace sidewall of the chord and the local buckling of the brace sidewalls. The permanent plastic deformations of the joints after the cooling process are illustrated in Figure 3.

For each specimen the temperatures and displacements were recorded, thus the temperature at which the joints failed was obtained. The temperature at which the joint is not able to withstand the applied loading is called the critical temperature. The measured values of the critical temperature during the tests for each joints are shown in Table 2. As documented in EN

1993-1-2 (2005) the yield strength of a steel element decreases under elevated temperatures. The standard provides values of the reduction factor for the effective yield strength to estimate the steel strength at given temperature. Table 2 summarizes the respective reduction factors for effective yield strength and final steel yield strength for the specimens based on the measured temperatures. Furthermore, the steel yield strength is substituted to Eq. (1-3) to obtain the design resistance of joint at the critical temperature, Table 2. It can be seen, that the joint resistance at the high temperature is significantly lower than the design values at the ambient temperature due to steel thermal properties. However, the applied load to the specimens differs from the design resistance values. The specimen *S1* sustained greater load than the design resistance, whereas specimens *S2* and *S3* failed subjected to lower load than the design value. This observation may lead to the conclusion, that joints with bigger β parameter are more sensitive to the temperature change than joints with smaller β parameter.

Table 2. Design resistance of specimens at high temperature.

Specimen	Design resistance of joint $N_{1,rd}$ (kN)	Applied load (kN)	Measured critical temperature (°C)	Reduction factor for effective yield strength	Yield stress (Yield strength) (MPa)	Design resistance of joint at high temperature (kN)
S1	80	24	730	0.194	81.5	19
S2	277	83	717	0.2096	88	108
S3	780	234	690	0.254	106.7	370

a) b) c)

Figure 3. Deformations of the specimens: a) *S1*; b) *S2*; c) *S3*.

4 Conclusions

This paper presents the experimental study on axial resistance of SHS T-joints under fire conditions. The novelty of the tests results allows one to draw the following results:

- The fire resistance of the specimens was calculated based on the rules of EN 1993-1-8 (2005) for ambient temperature design. It was shown, that the decrease of steel strength at elevated temperature is vast. The differences between the value of applied load and the calculated joint resistance at high temperature demonstrates that the rules cannot be applied without any modification. The method was used due to no other direct method available to estimate a fire resistance of the joint. The experiment illustrates also that joint geometries influence its fire performance.
- The failure mode for the specimens have been studied. From the experimental observation, it was found that the local buckling of the chord surface near the brace/chord intersection occurred. The failure mechanism for the specimen *S1* was to local buckling of the top chord wall, for the specimen *S2* the local buckling of the top chord and sidewalls and for the specimen *S3*with thick chord walls apart from the local buckling of chord sidewalls also the local buckling of the brace sidewalls was observed.

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