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# Experimental and numerical study on temperature distribution of square hollow section joints

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ABSTRACT

This paper presents the experimental and numerical results of a temperature distribution of the unprotected square hollow section (SHS) joints in a standard fire test. The experiment's programme included three fire tests in which six specimens with different joint configurations, T-, Y-, K- and KT-joint, and with different brace dimensions were examined. This paper introduces the idea of the application of component method calculations under fire conditions. The main goal of the study was to develop the temperature distribution in each component of the connection. During the tests, the temperatures in certain locations of the joint area were measured. The results indicated that the joint-area temperature field varies remarkably among different joint types. Hence, the joint should be divided into components with the same temperature distribution. This suggests that the component method for calculating the mechanical properties of structural joints at ambient conditions may be used to obtain the joint temperatures and as a consequence the behaviour of the whole unprotected steel structure. To develop the component method, a finite element (FE) model was used to simulate the joint behaviour under fire conditions. Experimental results have been used to validate and verify the numerical model created in Abaqus/CAE software to develop the equivalent component factor for each region of the joint in further studies.

## 1. Introduction

The crucial part of the tubular steel structure is the welded connection between the brace and chord members. The behaviour of the welded tubular joints has been investigated in detail under ambient conditions [1–3], but limited research is available that describes the joint performance under fire conditions. Using the current design guidance, it is difficult and time consuming to predict exactly what the relevant failure mechanisms and modes to be considered in the tubular joint design are. Little attention has been paid to the differences in the temperature distribution between the connected members and the influence of these temperature variations on the failure modes. A common practice in applying the design regulations of EN 1993-1-2 [4] has been to specify joint fire protection to match the fire protection thickness of the connected members [5]. This simple fire performance assessment is motivated by the assumption that in the joint region, due to a higher mass concentration and a comparatively low fire-exposure area, the temperature rises more slowly than the temperatures of the connected beams and columns do. It is then assumed that the reduction of the resistance due to a high temperature is smaller in joints in all cases. However, observations from the real fires, for instance, the full-scale fire tests at Cardington in 1994 [6], or the collapse of the World Trade Centre buildings in 2001 [7], have caused the change of the perception of the connection behaviour. These fires showed that joints in a structure are more vulnerable than first assumed. This is because the forces and deformations which act on a joint under fire conditions are different from those occurring at an ambient temperature.

Another approach to designing steel joints is the component method, where joints are decomposed into different components based on the assessment of the mechanical properties at each component to which a joint is divided. The component method is available in the current EN 1993-1-8 [8] for the open sections. For tubular sections, ongoing activities include the method in the next revision of EN 1993-1-8 [8], although more information is required to extend the method to fire conditions. First, the temperature distribution in the joint needs to be known to conduct more advanced calculation models, which will take into account the influence of the structure and the rise of the internal forces [9]. The experimental fire tests of the temperature distribution have been conducted by the Czech Technical University of Prague and the University of Manchester [10–14,5]. In their research Jána et al. [10–12] and Ding and Wang [5,13] focused on temperature change in the individual components of reverse channel section connected to concrete-filled tubular (CFT) columns. In [14], the temperatures of steel members and joint components in different unprotected

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**Table 1**
Geometric properties of the specimens.

| Test number | Specimen | Joint type | Chord (mm) | | Brace 1 (mm) | | Brace 2 (mm) | | Brace 3 (mm) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Width | Thickness | Width | Thickness | Width | Thickness | Width | Thickness |
| 1 | K1 | T- | 140.1 | 6.1 | 60.1 | 3.0 | 100.1 | 4.1 | – | – |
| | K2 | Y- | 140.2 | 5.9 | 60.2 | 3.0 | 100.2 | 4.0 | – | – |
| 2 | K3 | K- | 140.0 | 6.1 | 100.0 | 4.0 | 100.0 | 4.0 | – | – |
| | K4 | K- | 140.1 | 6.1 | 60.0 | 3.0 | 60.0 | 3.0 | – | – |
| 3 | K5 | KT- | 140.2 | 6.0 | 100.1 | 4.0 | 60.0 | 2.9 | 100.1 | 4.0 |
| | K6 | K- | 140.0 | 6.0 | 100.0 | 4.0 | 60.0 | 3.0 | – | – |

joint types (i.e. flush endplates, flexible endplates, fin plates and web cleats) were measured. All these studies indicated that the temperature distributions within the joint area are not uniform, the difference in temperatures is significant and that it may be necessary to consider the non-uniform distribution in the joint design methods. However, similar studies are not available for the temperature distributions of tubular square joints under fire conditions. Additionally, the main emphasis of hollow section research has been on circular cross-sections (CHS). The influence of a high temperature on the ultimate strength of CHS joints has been studied, inter alia, by Nguyen, Tan and Fung [15–19], who focused on T-joint connections. He et al. [20–22] tested the fire resistance of K-joints, giving special attention to the effect of geometrical parameters, heating properties and the loading ratio on the critical temperature of K-joints. Square hollow section (SHS) joints are considerably less examined. Yang et al. [23] conducted the general full-scale experimental tests for obtaining the fire resistance and the failure mode of the axially loaded joint from the displacement/temperature curve. Ozyurt et al. [24] presented another approach, investigating the limit loads for different types of connections (T-, Y-, X-, N-joints) with an SHS or CHS brace member in the numerical study. All of the abovementioned studies contain the results of loaded joints, and only the displacements of specimens are presented with no detailed information about the thermal distributions within the joints. In the research of Jána et al. [10–12] and Ding and Wang [5,13] an analytical calculation method was developed to obtain the temperature of the joint components within a reverse channel connected to a CFT column. Jána et al. [12] developed an analytical method to determine the temperature of the components of the reverse channel connection to steel concrete-filled column. The method was based on the Lumped Capacitance Method included in EN-1993-1-2 [4]. First, they divided the joint into sections of uniform temperature. Then by reducing fire emissivity factor, by developing the regression function to calculate the heat transfer at the steel tube and by modifying the section factor of the connection, they obtained a relatively good and safe prediction of heat transfer in the joint. However, the described method cannot be directly implemented to SHS welded joints due to the different geometrical joint configurations and details. Dai et al. [14] applied the same approach to connections between open sections and a CFT column. In [14], the analysis allowed to propose more accurate heat transfer coefficient and section factor for the simple fire design method of this type of connections.

The Fire Laboratory of the Tampere University of Technology has carried out an experimental fire research to produce information about the actual temperature distributions in the vicinity of the SHS brace-to-chord connections. This paper provides the description and results of the three fire tests used to obtain the thermal distribution histories of six specimens. The experimental research is introduced in Sections 2 and 3. For numerical simulations and studies, FE models of the connections have been developed and validated against the test results. The models and numerical analysis results are introduced in Section 4. The results reported in this paper form basis for further research aiming to develop an analytical calculation method to determine the temperatures of the joint components within SHS brace-to-chord connections. This information can then be incorporated into the design approach based on the component method.

## 2. Experimental test arrangements

### 2.1. Test specimens

Six SHS joints called K1-K6 were tested. All of the square steel tubes were fabricated from cold-formed S700 steel sections according to EN 10219-2:2006 [25]. The steel material properties are published in EN 1993-1-1 [26] and EN 1993-1-12 [27]. No fire protection exists on the steel elements. Table 1 provides a summary of the dimensions of the cross-sections used in the fire tests. Four types of joints were investigated in the test: T-, Y-, K- and KT-joints. Figs. 1–6 show the details of the specimens; the locations of the braces were designed according to EN 1993-1-8 [8]. In all specimens, the brace members were welded directly to the top flanges of the chord members.

### 2.2. Test setup

The testing furnace has a rectangular shape with internal dimensions of 3000 mm × 3000 mm × 1200 (height × width × depth). The test specimen was hung through the roof of the furnace. For the metal

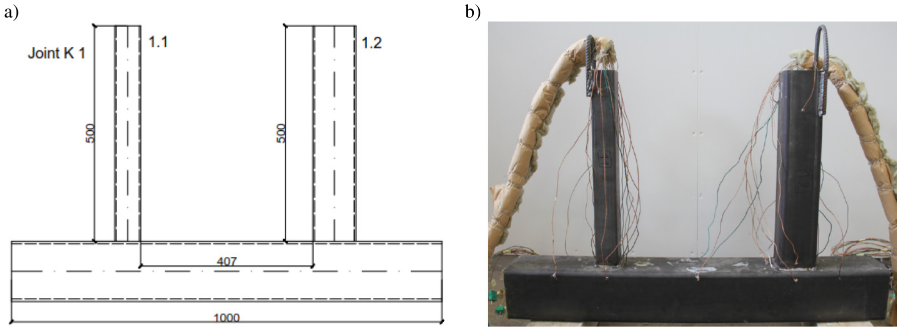

**Fig. 1.** Specimen K1: a) Drawing showing the joint details; b) tested joint with instrumentation.