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Mechanical properties of ultra-high strength (Grade 1200) steel tubes under cooling phase of a fire: An experimental investigation

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HIGHLIGHTS

- The post-fire behaviour of ultra-high strength steel (UHSS) is studied.
- The strength of UHSS after cooling from 600 °C to 450 °C was considerably reduced.
- The strength reduction after cooling was minor in high-strength and mild steel.
- Cooling rate effect on mechanical properties of UHSS cooled from 600 °C was minor.

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ABSTRACT

There has recently been a growing trend towards using ultra-high strength steel (UHSS) in many engineering applications. However, few researches have focused on the mechanical properties of this kind of steel at elevated temperatures. In this study, the mechanical properties of UHSS at temperatures characteristic of fire and after cooling from fire temperatures, are studied experimentally. The specimens taken from UHSS tubes are subjected to fire temperatures of up to 600 °C and tensile tests are carried out both at elevated temperatures and after the specimens were cooled to room temperature. As expected, the strength of the UHSS specimens decreases significantly when tested under fire temperatures of 450 °C and 600 °C. However, the strength of the UHSS is also considerably reduced after cooling down from high fire temperatures to room temperature. The stress–strain curves, strength and ductility of the UHSS tube specimens are discussed. Furthermore, in order to perform a comparison study, the stress–strain curves for three different grades of steel tubes including UHSS, high strength steel (HSS) and Mild steel (MS) tubes are presented and compared. It is shown that the reduction in the strength of the UHSS after cooling from fire temperatures of up to 600 °C does not occur to the same extent for HSS and MS steels. The effect of the cooling rate after exposure to fire temperatures on the mechanical properties of UHSS tube specimens is also investigated. Micro-structure examination is conducted using optical and scanning electron microscopy (SEM) and the room temperature strength reduction in the UHSS after exposure to the fire temperatures is discussed in terms of the effect on the steel microstructure. A recommendation has been made for separating studies of the effect of simulated fire temperatures on the residual strength of steel into two classes (low and high temperature), depending on whether a critical maximum temperature (which depends on alloy composition) is exceeded and the science underlying this recommendation has been discussed.

1. Introduction

During the past decades, ultra-high strength steel (UHSS) tubes with nominal yield strengths of up to 1200 MPa have been widely used in the automotive industry due to the increased tensile strength and high energy absorption which leads to the weight and cost reduction and improvement of road safety issues [1–5]. Presently, due to construction development, the demand for using high strength steel in civil engineering applications is also increasing [6–10]. However, due to the lack of relevant design codes of practice covering the behaviour of UHSS under extreme actions, limited application of this kind of steel is seen in construction industry around the world. In order to utilise UHSS tubes in civil

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engineering applications, their behaviour under various loading scenarios including fire, cyclic, impact, etc. must be investigated. This paper addresses the mechanical properties of UHSS tubes under the cooling phase of a fire.

When only partial damage or no damage occurs during an extreme action, it might be possible to reuse the structural member [11–17]. However, after a structure is cooled down from a fire temperature, residual stresses may be developed [18]. In order to develop a rational thermal analysis in which the effect of residual stresses are taken into account, investigating the mechanical properties of the material under cooling phase of fire is essential.

One of the primary models developed to describe the behaviour of structural members during the cooling phase of a fire was introduced by El-Rimawi et al. [19]. In this study, the available stress–strain curves for the steel materials at elevated temperatures were employed and by adopting a bi-linear unloading curve and applying some modifications, a simple model was developed to describe the cooling path of structural members. Bailey et al. [20] developed a model in which a curvilinear unloading path, instead of the bi-linear one proposed by El-Rimawi et al. [19], was adopted. Furthermore, it was assumed that the cyclic loading of steel members in a fire does not occur which allows the definition of a unique and reversible unloading path. According to the results presented in [19], it can be observed that compared to El-Rimawi's model, Bailey's model results in a lower absolute value of the permanent strain and thus a greater recovery of displacement. However, neither of these two models were validated with experimental results. Wang et al. [21] developed a numerical model for steel structures during the cooling phase. They provided a simple model describing the unloading path during the cooling phase by using a line and a half of the original stress–strain curve. The model was implemented into a computer program developed by the authors and a steel truss was analysed using the presented model to demonstrate the residual deformations and stresses developed in the structures after a fire. However, due to the lack of experimental data on this topic, the results were only verified by using ANSYS finite element software.

In order to investigate the remaining strength of steel structures exposed to fire, Outinen [22] carried out tensile tests on different grades of structural steel materials including S355, S460M, S350GD+Z, S355J2H and EN 1.4301. The tensile coupons were cooled to room temperature from fire temperatures of up to 1000 °C. The stress–strain curves for the coupons taken from flat and corner regions of cold-formed steel tubes were presented by the author and their post-fire behaviour was discussed. Qiang et al. [23] performed a set of tests to investigate the behaviour of S460 steel under fire and post-fire conditions. In this research, in order to study the post-fire behaviour of the material, they heated the steel specimens to fire temperatures of up to 1000 °C and then performed tensile tests at room temperature after cooling the specimens. The residual elastic modulus, yield strength and ultimate tensile strength of S460N steel after cooling down from fire temperatures were reported. It was shown that S460 steel regains at least 70% of its original mechanical properties. The same authors performed a similar study on high strength steel S960 [24]. The results indicated that post-fire behaviour of S960 steel is different to S460 steel. Comparing the results obtained for S460 and S960 steel specimens cooled from temperatures above 600 °C to room temperature, a sharper reduction in residual yield strength and ultimate tensile strength of S960 was observed. Moreover, the mechanical properties of both S960 and S460 steel are only affected by the cooling phase when they are subjected to fire temperatures above 600 °C.

The effect of cooling from fire temperatures on the mechanical properties of the steel connectors such as bolts has also been investigated. Hanus et al. [25] performed steady-state tests at various temperatures after heating Grade 8.8 bolts to 800 °C and then cooling them at a rate of 10–30 °C/min [25]. They also developed an analytical model for the stress–strain behaviour of bolts during a natural fire which gives values of strength reduction factors for the cooling phase.

Research on the mechanical properties of ultra-high strength steels with nominal yield strengths above 960 MPa at elevated temperatures is limited and the behaviour of UHSS tubes during the cooling phase of a fire has not so far been investigated. Heidarpour et al. [26] presented an experimental study on UHSS (Grade 1200) tubes subjected to elevated temperatures of up to 600 °C and the changes in strength and ductility were discussed. The results showed a dramatic deterioration in strength of the UHSS after 300 °C. They also proposed some equations to describe the reduction factors of 0.2% proof stress and ultimate tensile strength for UHSS tubes at fire temperature.

This paper addresses the mechanical properties of ultra-high strength steel during the cooling phase of a fire. Although the nominal tensile strength of UHSS studied by Heidarpour et al. [26] is close to that of the alloy used in this study, due to differences in chemical composition as well as manufacturing process, experimental tests at elevated temperatures are also carried out on the UHSS specimens in this study. Therefore, two sets of experimental tests are carried out. The first set of tests are heat-up tests where the specimens taken from UHSS tubes undergo strain-controlled tensile tests at elevated temperatures. The second set of tests, which forms the main focus of this study, includes the cooling tests where the tensile test is carried out at room temperature on UHSS specimens after being cooled down from fire temperatures. In these latter tests, the changes in strength and ductility of the material are discussed. In order to compare the change in the material properties of the UHSS tubes with those of high-strength steel (HSS) and Mild-steel (MS) tubes, experimental tests were also carried out on tensile coupons taken from HSS and MS tubes. In addition, the effect of cooling rate from simulated fire temperatures on the mechanical properties of UHSS tube specimens cooled down from 600 °C is also investigated. Finally, using the optical and scanning electron microscopy (SEM), microstructure examinations are performed on the bulk microstructures of the tested specimens and the relationship between the changes in microstructure and the changes in mechanical properties after fire temperature exposure are discussed.

2. Experimental tests

2.1. Test specimens

The test specimens are taken from ultra-high strength steel (Grade 1200), high strength steel (Grade 800) and Mild-steel (Grade 350) cold-formed tubes with nominal diameter and wall thickness of 76.1 mm and 3.2 mm, respectively. The geometry of the test specimens is shown in Fig. 1 and the samples are sectioned from the tubes using high pressure water jet cutting. The shape and dimensions of the specimens are determined in agreement with the limitations defined in ASTM E8 [27]. As shown in Fig. 2, the specimens were taken from two strips located at right angles (900) to the tube weld line. For the sake of comparison, some tests are also performed on the UHSS specimens taken from the opposite face (1800). In order to grip the end of the specimens for the tensile tests, they are mechanically flattened according to the instructions provided in AS1391 [28].

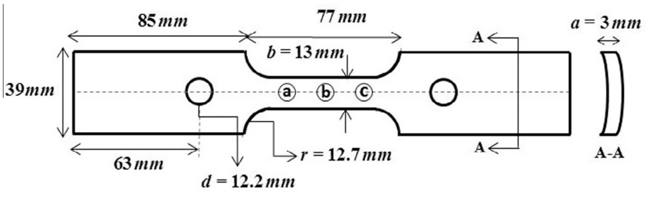

Fig. 1. The test specimens geometry.