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Post-fire mechanical response of ultra-high strength (Grade 1200) steel under high temperatures: Linking thermal stability and microstructure

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ABSTRACT

Recently, ultra-high strength steel (UHSS) tubes with nominal yield strengths of up to 1200 MPa have attracted attention for applications in engineering fields. While many studies have focused on the mechanical behaviour of mild carbon steel at elevated temperatures, there is a scarcity of data for the in-fire and post-fire mechanical response of the UHSS material. In this study, the tensile mechanical properties of the UHSS tube under fire and after cooling from fire temperatures of up to 800 °C to room temperature are studied. The stress-strain curves, strength and ductility of the UHSS material are discussed. It is shown that the in-fire strength of the UHSS tube starts to deteriorate when the specimens are exposed to fire temperatures above 300 °C and is almost disappeared when tested at 800 °C. There is also a major reduction in the strength of the UHSS tube specimens cooled from fire temperatures above 470 °C to room temperature. To investigate the effect of steel grade on the in-fire and post fire mechanical behaviour of steel materials, the stress-strain curves of Grade 800 high strength steel (HSS) tube specimens are presented and compared with those obtained for Grade 1200 UHSS tube. In order to interpret the experimental results, microstructural examination on the UHSS is conducted using optical and scanning electron microscopy (SEM). The plots of the thermodynamic stability of the ferrite and cementite phases in the UHSS and HSS are calculated and the phase changes occurring during each fire temperature exposure are discussed. Based on the results obtained from experimental tests, an empirical constitutive model which takes into account the post-fire behaviour of UHSS material is developed. The constitutive model can be implemented into commercial finite element packages to carry out a rational thermal analysis and perform fire safety design and evaluation.

1. Introduction

In recent years, ultra-high strength structural steels (UHSS) have been offered by steel manufacturing companies. Due to the high specific strength of these materials, their application in the automotive industry has been increasing to reduce the weight of automobiles [1–3]. Recent research conducted on UHSS indicates that this type of steel has also a great potential to be introduced as a structural material in civil engineering applications [4–10]. Using UHSS in structural engineering can lead to savings in engineering work, labour and transport costs since lighter lifting equipment and fewer people may be needed at the construction site. Moreover, UHSS may enable the structures to be constructed considerably lighter than usual. Although UHSS with nominal yield strength of 1200 MPa has promising properties for civil engineering applications, there is still lack of knowledge about the behaviour of this material under extreme structural loadings such as fire, earthquake, impact and blast. Fire is considered to be one of the severe hazards which may occur individually, or followed by another extreme action [11–15], and can significantly damage the structure during its service life. In order to perform a rational analysis on the steel structural members made of UHSS subjected to fire temperatures, understanding their constitutive material behaviour after exposure to elevated temperatures is necessary.

A number of researchers have focused on the in-fire and post-fire mechanical behaviour of structural steels [7,16–22]. Outinen [18] investigated the in-fire and post-fire mechanical properties of S355 cold-formed steel. The results showed that even after the steel specimens are cooled from fire temperatures of up to 700 °C, their yield strength is still the same as that of the virgin material. Qiang et al. [19,20] performed a set of experimental tests to investigate the behaviour of S460, S690 and S960 steels under fire and post-fire conditions. In order to study the post-fire behaviour of these three steel grades, the specimens were heated to fire temperatures of up to 1000 °C and then performed quasi-static tensile tests at room temperature after cooling the specimens. The

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changes in the yield strength and ultimate strength of test specimens after cooling down from fire temperatures were studied. Their results showed that the aforementioned mechanical properties are only affected by the cooling phase when they are subjected to fire temperatures above 600 °C. Moreover, the stronger the tested steel was, the more deterioration in its mechanical properties occurred when cooled from elevated temperatures. Chiew et al. [16] studied the in-fire and post-fire mechanical properties of the reheated, quenched and tempered high strength S690 steel plate (RQT-HSS-S690). They studied the changes in the 0.2% proof stress, 2.0% stress and ultimate strength of the RQT-S690 HSS plate at elevated temperatures of up to 1000 °C and after being cooled to room temperature. According to their results, the residual strength properties of the RQT-S690 HSS specimens after being cooled from temperatures above 400 °C are considerably reduced. Wang et al. [21] evaluated the ultimate strength, elongation and the elastic modulus of the high strength Q460 steel (HSS-Q460) after being cooled from fire temperatures of up to 900 °C to room temperature. In order to cool down the test specimens, they applied two cooling methods: natural air cooling and cooling by water. Their results showed that when the HSS-Q460 specimens are cooled from temperatures below 700 °C, their mechanical properties are almost unchanged. However, for specimens cooled from higher temperature exposures, up to 30% reduction in strength results was observed. In addition, they concluded that the cooling method has a significant influence on the ultimate strength and elongation of the HSS-Q460. Heidarpour et al. [23] investigated the in-fire mechanical properties of the UHSS (Grade 1200) tubes subjected to elevated temperatures of up to 600 °C. Their results showed that the strength of the UHSS is considerably deteriorated when tested at temperatures above 300 °C. Using the experimental results, they proposed a set of predictive equations describing the reduction factors of 0.2% proof stress and ultimate tensile strength for the UHSS tubes at fire temperature of up to 600 °C.

From the literature review it can be understood that in all studies focusing on the post-fire mechanical behaviour of steel materials, depending on the grade of the tested steel, the effect of cooling phase of a fire is significant when temperature increases above a critical temperature. This phenomenon was discussed by Azhari et al. for different grades of steels [7]. Based on the plots of the thermodynamic stability of the phases present in the microstructure of the UHSS and HSS, the fire temperature exposures are classified in two groups: Low fire temperatures and high fire temperatures. Considering that temperatures below 600 °C are classified as low fire temperatures category for the ultra-high strength steel (UHSS), an experimental study was performed on the UHSS (Grade 1200) tubes subjected to low fire temperatures and the changes occurred in their strength and ductility at elevated temperatures of up to 600 °C and after being cooled to room temperature were discussed [7]. The results showed that while there is a significant reduction in the strength of the UHSS specimens tested under fire temperatures of 450 °C and 600 °C, the residual strength of the UHSS is also considerably reduced after cooling from these temperatures.

Although studies have been conducted on the post-fire mechanical behaviour of mild steel (MS) and high strength steel (HSS), the effect of cooling phase of a fire on mechanical properties of the Grade 1200 ultra-high strength steel (UHSS) subject to high fire temperatures (i.e. above 600 °C) has not been investigated. This paper addresses the in-fire and post-fire mechanical properties of the UHSS (Grade 1200) tube specimens subjected to fire temperatures of up to 800 °C.

Two sets of experimental tests are carried out in this work. The first set includes heat-up tests where the specimens from the UHSS tubes are subjected to tensile tests at fire temperatures of up to 800 °C. The second set includes the cooling tests where the quasi-static tensile test is carried out at room temperature on the UHSS specimens after being cooled from fire temperatures. The changes occurring in the mechanical properties of the material, including strength and ductility, in these two sets of tests are discussed. In order to investigate the effect of steel grade on the in-fire and post-fire mechanical properties of steel, the same tests are also conducted on specimens taken from high strength steel (HSS) tubes with nominal yield strength of 800 MPa. The effect of the elevated temperature exposure on the microstructure of the specimens cooled from temperatures above 700 °C (high fire temperatures) is evaluated using optical microscopy and scanning electron microscopy (SEM) methods and the microstructural reason for the mechanical tests results are explained. The thermodynamic stability of the ferrite and cementite phases in the UHSS and HSS obtained by the authors [7] is studied and the reason behind the residual strength reductions are explained based on the phase changes occurring in the steel material during fire. Finally, based on the data obtained from the experimental tests, an empirical constitutive description is developed to predict the stress-strain response of the UHSS materials cooled from fire temperatures of up to 800 °C to room temperature.

2. Experimental tests

The work recently performed by the authors [7] was limited to the investigation of the in-fire/post-fire mechanical behaviour of Grade 1200 ultra-high strength steel (UHSS) subjected to fire temperatures up to 600 °C. Since it is expected that the residual mechanical properties of UHSS should exhibit a discontinuous alteration after exposure to temperatures above ∼700 °C, in this paper experimental tests are performed to evaluate the mechanical behaviour of UHSS tubes at fire temperatures above 600 °C, known as high fire temperatures, and after being cooled to room temperature. For comparison purposes, the experimental tests are also carried out on Grade 800 high strength steel (HSS) tube material.

2.1. Test specimens

The chemical compositions of Grade 1200 and Grade 800 steels considered in this paper and their manufacturing process are similar to those presented in Ref [7]. The test specimens were sectioned from the UHSS and HSS tubes using high pressure water jet cutting with nominal external diameter of 76.1 mm and wall thickness of 3.2 mm. As shown in Fig. 1, the shape and dimensions of the specimens are determined in accordance with ASTM E8 [24]. The specimens are cut from two strips located at right angles (90°) to the tube weld line as indicated in Fig. 2.

In order to fit the samples into the grips for the tensile tests, they are mechanically flattened based on the instructions given in AS1391 [25]. Each test is repeated until the results obtained from two similar tests have a difference of less than 3%. The cross sectional area of the gauge length of the test specimens is determined according to AS1391 [25].

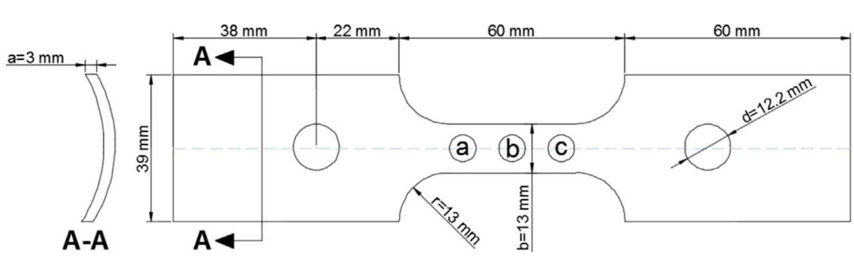

Fig. 1. Dimensions of test specimens.