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Effect of creep strain on mechanical behaviour of ultra-high strength (Grade 1200) steel subject to cooling phase of a fire

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HIGHLIGHTS

- Creep effect on post-fire behaviour of ultra-high strength steel (UHSS) is studied.
- Multi-phase experimental tests are performed to explore sustained load effect.
- Microstructural origin of accelerated softening due to creep is discussed.
- Creep has a considerable effect on UHSS cooled from temperatures above 470 °C.
- Effect of creep on thermal properties of UHSS is more pronounced than mild-steel.

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ABSTRACT

This paper evaluates the mechanical behaviour of Grade 1200 ultra-high strength steel (UHSS) tube under a multi-phase loading scenario including fire and creep. To achieve this, two sets of experiments are performed on standard dog-bone specimens taken from UHSS tubes. In the first set of experiments, termed Creep-Heat-up tests, the specimens are axially loaded to a specific stress level, f_s. Whilst the axial load is maintained, the samples are heated to elevated temperatures of up to 700 °C and a tensile test is performed on them at elevated temperature. The second set of experiments, which are the main focus of this study, are termed Creep-Cooling tests and are similar to the first set except that the specimens are tested to failure after being cooled to room temperature. The axial load in this set of tests is maintained during both heat-up and cooling phases of a fire. The stress-strain curves, the creep strain the specimens experience due to the sustained axial load during fire, and the residual strength of the test specimens are discussed. In order to investigate the effect of steel grade, Grade 800 high strength steel (HSS) and Grade 350 mild steel (MS) specimens are also tested and the results are compared. Finally, the microstructural origin of accelerated softening in UHSS due to creep strain is discussed.

1. Introduction

During the past decades, the high strength and energy absorption characteristics of ultra-high strength steels (UHSS) have made steel manufacturing companies interested in offering these materials to the automotive industry. The high strength to weight ratio of UHSS means they may also have some potential to be used in structures to produce energy efficient members. Innovative fabricated columns composed of ultra-high strength steel (UHSS) tubes with nominal yield strength of 1200 MPa have recently been proposed [1–3]. The superior mechanical properties of these columns show the potential of UHSS to be used as a structural material.

The behaviour of steel structures under different loading scenarios have been widely investigated, e.g. [4,5]. Nevertheless, to ensure the safety and durability of the structure, it is also necessary to understand the behaviour of construction materials under extreme events such as fire [6]. However, there is currently a lack of relevant design codes accounting for the behaviour of Grade 1200 UHSS under fire conditions in the available steel standards.

A fire has two main phases: the heat-up phase where the temperature reaches its peak, and the cooling phase, where the fire enters its decay stage and the temperature reduces to ambient. In order to analyse a structure subjected to fire, it is necessary to understand the behaviour of the construction material under both heat-up and cooling phases. When a structural member survives the heat-up phase of a fire and is cooled to room temperature, its residual strength determines whether or not it is reusable. In

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recent years, there has been a great focus on evaluating the mechanical behaviour of steel at elevated temperatures [7–12]. Comparatively fewer works have focused on the behaviour of steels after being cooled from fire temperatures [13–17]. Regarding the mechanical behaviour of UHSS under fire conditions, an experimental study on coupons taken from UHSS (Grade 1200) tubes subjected to low fire temperatures (up to 600 °C) [18] as well as high fire temperatures (up to 800 °C) [19] has recently been performed. The changes occurring in the tensile mechanical properties of UHSS at elevated temperatures and after being cooled to room temperature were discussed.

When a fire hazard occurs in a structure, in addition to the severe changes of the structural members due to thermal loading, the sustaining loads (such as dead loads, live loads, etc.) may also affect the in-fire (elevated temperature) and post-fire (ambient) mechanical response of the structural material. In order to simulate fire loading of the steel, the mechanical loads present during the fire must also be considered. In other words, during a real fire in a structure, the temperature is increasing to its peak and decreasing to room temperature while the structural member is subjected to mechanical loads. This may cause creep in which the strain in a structural member varies under load [20]. Consequently, assuming that during the heat-up and cooling phases of fire, the load applied to the structural members are sustained, a study of the thermal creep of the material along with its effect on the mechanical response under temperature variations is necessary to simulate a real fire situation.

Many researchers have investigated the creep failure of steel subjected to elevated temperatures [21–27]. Morovat et al. investigated the creep behaviour of ASTM A992 steel at elevated temperatures [27]. They reported that creep is significantly dependant on the temperature and stress level of the material during fire. Brnic et al. evaluated the creep behaviour of high-strength low-alloy steel at elevated temperatures. They carried out uniaxial creep tests for different elevated temperatures and different loads [22]. The same authors performed an experimental study on the behaviour of heat-resistant austenitic steel subjected to uniaxial stress at elevated temperatures of up to 800 °C and investigated its creep resistance at different temperatures for different loads [21].

In the present work, in order to simulate the behaviour of UHSS (Grade 1200) during the cooling phase of a fire, tensile coupons taken from UHSS tube specimens are subjected to a sustained tensile axial load (F_s) during both heat-up and cooling phases of fire and strain-controlled tensile tests are subsequently performed. Unlike the previously mentioned researches where the steel material was subjected to creep failure at elevated temperatures, in the present study, the UHSS is not subjected to creep failure. Although creep occurs in the UHSS during the heat-up and cooling phases of fire, the material is failed by performing tensile tests of the test specimens so that the residual strength after creep can be quantified. Similar multi-phase studies were conducted on concrete filled steel tube and reinforced concrete under compression loads [28,29]. In these works, they applied different constant loads to the specimens and increased the temperature while the load was maintained, then performed compression tests on test specimens until failure.

In the present study, two sets of tests are performed: Creep-Heat-up tests and Creep-Cooling tests. The Creep-Heat-up tests investigate the effect of creep on mechanical behaviour of UHSS (Grade 1200) at elevated temperatures. The Creep-Cooling tests, which are the main focus of this work, evaluate the effect of creep on mechanical behaviour of UHSS subject to cooling phase of a fire. The variation in creep strain, the stress-strain curves obtained from the tensile tests and the residual strength of the UHSS specimens after different tests are calculated and discussed.

In order to evaluate the effect of steel grade, the same tests are performed on samples of Grade 800 high strength steel (HSS) and Grade 350 mild steel (MS) tube specimens and the results are compared with those of UHSS specimens. For the HSS and MS materials, after being cooled from temperatures of up to 600 °C to room temperature their strength remain relatively unchanged [18]. Therefore, the maximum fire temperature considered for them is 700 °C. The microstructural origin of the accelerated softening in UHSS due to the creep strain occurring during elevated temperature loading is characterised using Scanning Electron Microscopy (SEM) and the physical origin of the softening is discussed.

2. Experimental tests

2.1. Test specimens

Three grades of steel tubes are considered in this study: Grade 1200 ultra-high strength steel (UHSS), Grade 800 high strength steel (HSS) and Grade 350 mild steel (MS). The chemical compositions of these materials are shown in Table 1. Due to the lack of knowledge about the behaviour of UHSS under fire and creep, and also its high sensitivity to elevated temperature exposures [18], this steel is the main focus of this study and the HSS and MS tubes are tested for the purpose of comparison. Standard dog-bone test specimens are extracted from the steel tubes using water-jet cutting. The nominal diameter and wall thickness of all tubes are 76.1 mm and 3.2 mm, respectively. The geometry and location of the specimens sectioned from the steel tubes are illustrated in Fig. 1.Using the instructions provided in AS1391 [23], the ends of the test specimens are mechanically flattened to be gripped for the tensile test. The cross section area (S_0) of the gauge length of the test specimens is calculated by [23]:

$$S_0 = \frac{b}{4}(D^2 - b^2)^{\frac{1}{2}} + \frac{D^2}{4}\arcsin\frac{b}{D} - \frac{b}{4}[(D-2a) - b^2]^{\frac{1}{2}} - \left(\frac{D-2a}{2}\right)^2 \arcsin\frac{b}{D-2a} \tag{1}$$

in which, b and a are the width and thickness of the specimen gauge length (Fig. 1a) and D is the tube diameter.

2.2. Test method

Two sets of experimental tests, Creep-Heat-up tests and Creep-Cooling tests are performed to investigate the mechanical behaviour of UHSS under the multi-phase loading scenario of creep and fire.

2.2.1. Creep-Heat-up tests

In this set of tests, the test specimen is first loaded to the tensile load of F_s using the Instron 5982 100 kN testing machine on which a SF-16 split furnace is installed (Fig. 2). F_s is defined as the sustained axial load applied to the specimen and is obtained from $F_s = f_s S_0$, where S_0 is the cross sectional area of the specimen (Eq. (1)) and f_s is determined by

$$f_s = \beta f_{u,T} \tag{2}$$

In Eq. (2), $f_{u,T}$ is the ultimate tensile strength of the test material at elevated temperature T and β is the sustained axial load ratio.The furnace is subsequently set to the target fire temperature T and is switched on. During the heat up, the testing machine is operating under load control so that the upper jaw of the machine could displace to accommodate the thermal expansion of the specimen while the load remains constant at F_s. Once the temperatures of the three thermocouples attached to three points a, b and c on the specimen's gauge length (Fig. 1) are stabilized at the target temperature T, the