TRANSIENT STRESS-STRAIN CURVES OF ULTRA-HIGH STRENGTH STEEL TUBES AT HIGH TEMPERATURES INCORPORATING THERMAL CREEP EFFECTS

MOHAMMAD AMIN FARMANI[1], ZIJING LEI[1], AMIN HEIDARPOUR[1,*]

and XIAO-LING ZHAO[2]

[1]*Department of Civil Engineering, Monash University, Melbourne, VIC 3800, Australia*

E-mail: mohammadamin.farmani@monash.edu
E-mail: zlei0006@student.monash.edu
*E-mail: *amin.heidarpour@monash.edu*
[2]*School of Civil and Environmental Engineering, The University of New South Wales, Sydney, NSW 2052, Australia*
E-mail: xiaolin.zhao@unsw.edu.au

In contrast to room temperature, at high temperatures above 400 °C, significant time-dependent deformations occur in steel materials. Known as "thermal creep", this material behavior should be consisered in the fire design of steel structures. According to EUROCODE 3-1-2, the creep strains occurring in the event of a fire are generally not explicitly taken into account in the design procedure, but they are implicitly included in the transiently-determined material laws. Accordingly, by conducting transient tensile tests at temperatures of up to around 800°C on standard coupons taken from a 3.2 mm thick Grade 1200 ultra-high strength steel tube, this paper investigates the fire-temperature mechanical properties of these tubular elements. To better simulate structural fire conditions, in a transient heating regime, the temperature is steadily increased when the specimen is subjected to a constant tensile load. From the coupon tests, temperature-strain curves are obtained, wherein the strain contains all mechanical-, thermal- and time-dependent strain fractions. The temperature-strain curves are then converted to elevated-temperature stress-strain diagrams suitable for the fire design applications. Taking the thermal creep of UHSS into account, the results clearly differ from those of the steady-state tests previously conducted on the same UHSS tubes.

Keywords: Stress–strain curve; Fire; Transient test; Ultra-high strength steel; Steel tube; Thermal creep

1 Introduction

Considering the exceptional features of ultra-high strength steel (UHSS) in terms of strength, energy dissipation, and weight saving, researchers have attempted to use UHSS tubes in civil construction. In this respect, for example, Javidan et al. (2016) have recently introduced a new generation of fabricated steel columns consisting of mild-steel plates connected to UHSS tubes, with a nominal yield strength of 1200MPa, at the corners. The superior performance of these innovative steel columns indicates the enormous potential of UHSS tubes to be utilized in the production of sustainable structural components. However, due to the lack of relevant design codes of practice covering the behavior of UHSS tubes under extreme actions such as fire, their

Proceedings of the 17th International Symposium on Tubular Structures.
Editors: X.D. Qian and Y.S. Choo

Published by Research Publishing, Singapore.
ISBN: 978-981-11-0745-0; doi:10.3850/978-981-11-0745-0_046-cd

application in the construction industry is currently infrequent. In the building design process, one of the essential safety requirements which need to be satisfied is the provision of appropriate fire resistance to the structural components. However, constitutive equations provided in Eurocode 3-1-2 (2005) for steel at high temperatures are only valid for steel grades with a yield strength of up to 690 MPa. Hitherto, a number of researchers have studied the mechanical behavior of high strength and ultra-high strength steels at elevated temperatures. Chen et al. (2006) provided some insights into the behavior of higher grade steels at elevated temperatures by testing a high strength steel approximately equivalent to EN 10137-2 Grade S690Q at elevated temperatures. Based on the tests carried out by Qiang et al. (2013) on high strength steel at elevated temperatures, predictive equations for elastic modulus, yield strength, and ultimate strength were proposed which better suited the properties of high strength steel compared to mild steel. Heidarpour et al. (2014) conducted a detailed experimental study at elevated temperatures up to 600 °C, on the material properties of UHSS tubes with a nominal proof stress of around 1200-1300 MPa. They also proposed equations to predict the yield strength and ultimate strength reduction factors of the UHSS for the temperature range in question. More recently, Azhari et al. (2017) studied the tensile mechanical properties of Grade 1200 UHSS tubes at elevated temperatures up to 800 °C and after cooling down to room temperature. However, these experimental studies on the UHSS tubes have been conducted using a steady-state testing method, in which thermal creep effects have been neglected.

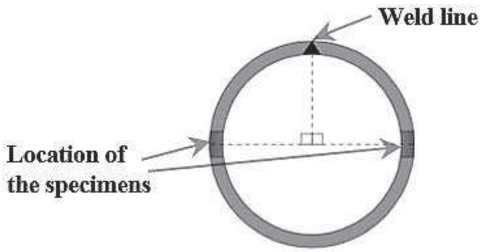
Creep is defined as the time-dependent plastic deformation of a solid material under load. In practice, structural steel shows no creep deformation at room temperature. However, experimental observations show that creep in metals including steel becomes significant when the temperature of the material exceeds 0.4-0.5 of its absolute melting temperature. Therefore, for steel members, thermal creep should be a design consideration for temperatures around 400°C and above and cannot be ignored in the structural fire design (Kodur et al. 2015). According to EUROCODE 3-1-2 (2005), the creep strains occurring in the event of a fire are implicitly included in the transiently-determined material laws. In a steady-state test, the material specimen is first heated up to the target temperature, and afterwards, while the temperature is kept constant, load or displacement is increased until the specimen fails. In practice, the steady-state test is relevant to the structures such as steel boilers which are exposed to constant high temperatures. During a structural fire event, however, components of the building are subjected to a transient regime of heating during which the temperature increases with time. As an alternative to the steady-state experiments, high-temperature material tests can also be carried out using a transient approach, where the specimen is subjected to a constant load and an increasing temperature until the occurrence of failure. It is anticipated that the transient testing approach would deliver more realistic results for structural fire engineering applications. Unlike the steady-state tests, in the stress-strain diagrams obtained from the transient tests, the thermal creep behavior of the steel is implicitly considered.

In this study, for the first time, material properties of Grade 1200 UHSS tubes at fire temperatures are experimentally derived using the transient approach. To this end, standard coupons are extracted from 3.2 mm thick UHSS tubes and tested at various stress levels while being heated up to fire temperatures of up to 800 °C. Stress-strain diagrams obtained from the transient tests are then compared to the results of the previous steady-state experiments on the same UHSS tubes.

2 Experimental tests

2.1 *Specimens*

To investigate the effect of creep on mechanical properties of Grade 1200 UHSS tubes at high-temperatures, tensile coupon tests were carried out under a transient heating condition. To have minimal effect on the mechanical properties of specimens through the cutting procedure, the water jet technique was used to take material coupons. The dog-bone specimens were extracted from two strips located at right angles (90˚) to the tube weld line of the UHSS tubes with a nominal external diameter of 76.1 mm and a wall thickness of 3.2 mm. Standard sub-size coupon according to the recommendations specified by ASTM E8/E8M (2016) was chosen for the dog-bone material specimens so as to ensure having a uniform temperature distribution over the gauge length during the test. The shape and dimensions of the coupons as well as their location in the UHSS tubes are shown in Figure 1.



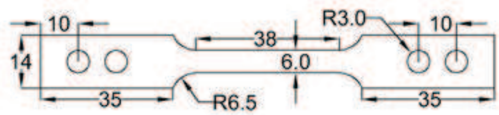
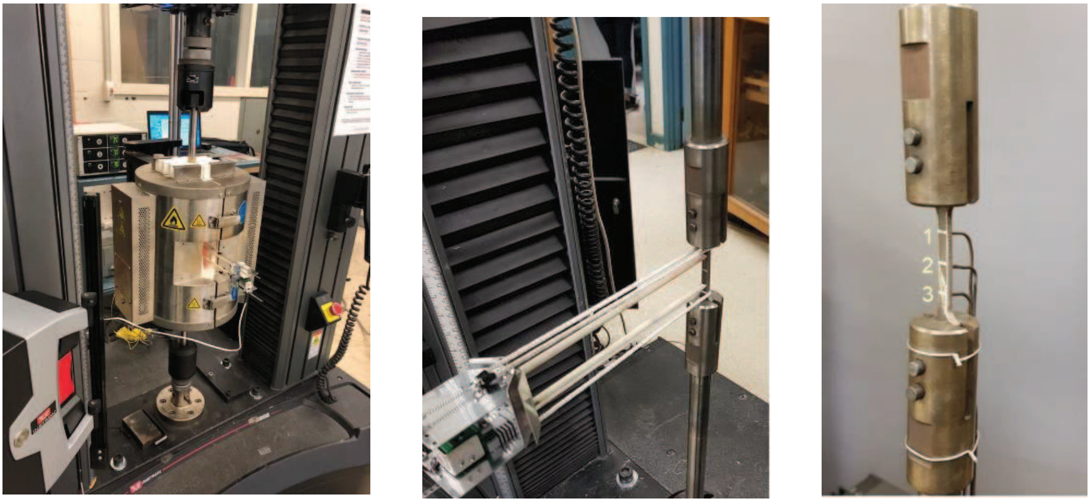


Figure 1. a) Tube section and b) dog-bone specimens (nominal dimensions in mm)

2.2 *Methodology*

Transient tests were carried out at 11 different stress levels varying from $0.05F_y$ to $1.0F_y$, where F_y is the nominal yield stress of the UHSS tubes at room temperature, i.e. 1200 MPa; hence, tests were conducted at 60, 120, 240, 360, 480, 600, 720, 840, 960, 1080, and 1200 MPa. The test setup is shown in Figure 2. For each test, the specimen was first loaded to the desired stress level using an Instron 5982 100 kN testing machine on which a three-zone SF-16 split furnace was mounted. The loading machine was set to operate under load control so that the load remained constant during the transient test. The model 3448 High-Temperature Contact Extensometer with a 25 mm gauge length was attached to the specimen to measure the strain during the test. As shown in Figure 2c, three Type N thermocouples labeled as T1, T2, and T3, were also attached to the specimen over its gauge length. The output wires of the thermocouples were connected to the furnace controller to directly control the temperature of the specimen, and a constant heating rate of 10 °C/min was chosen for the tests. Assuming an approximate failure temperature of 600 °C, this heating rate corresponds to a one-hour fire-resistance rating and is often used for transient tests on steel materials.

To ensure the consistency of transient tests, one of the major challenges was to accurately control the heating rate of the specimen. The furnace had three separate zones of heating elements each controlled by a Eurotherm 2416 controller using a PID control loop mechanism. Tuning these three controllers simultaneously so that a constant heating rate is obtained over the gauge length of the specimen was challenging as it involved manual re-setting the input parameters of the controllers through trial and error. Figure 3 shows the temperature measurements of thermocouples T1-T3 for a typical specimen tested. As seen, a great agreement is observed between the thermocouple readings, showing a uniform temperature distribution over the gauge length of the sample. From Figure 3, it is seen that the temperature varies linearly with time at a relatively constant rate of 10 °C/min as expected.



(a) (b) (c)

Figure 2. Test setup a) SF-16 split furnace mounted on the Instron 5982 100 kN loading machine, b) self-supporting contact extensometer connected to the sample, c) Thermocouples attached to the specimen

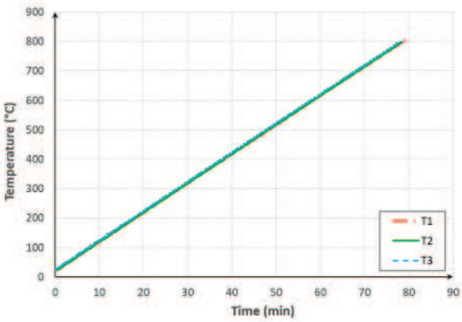


Figure 3. Thermocouple readings of a typical specimen

3 Results and Discussion

The result of the transient tests is a set of strain-temperature curves at different stress levels. Figure 4 plots the strain measured by the contact extensometer versus the temperature at each stress level. It should be noted that for each stress level, the test was repeated twice and the values reported here are the mean measurements. Depending on the applied stress, the diagrams have different initial strains at room temperature, i.e. 25°C. All curves, however, show a similar trend; as the temperature increases, both strain and strain rate experience a gradual growth followed by an exponential rise that eventually leads to the failure of the sample. In agreement with the custom practice for fire design, the critical temperature (or failure temperature) can be defined as the vertical asymptote of the strain-temperature curve (Maljaars et al. 2008). It is clear from Figure 4 that applying a higher stress to the sample would lead to a lower critical temperature; for example, when the stress level is $0.5F_y$ (600 MPa), the critical temperature is 555 °C, and it decreases by more than 100 °C to 447 °C when the stress level is $0.8F_y$ (960 MPa).

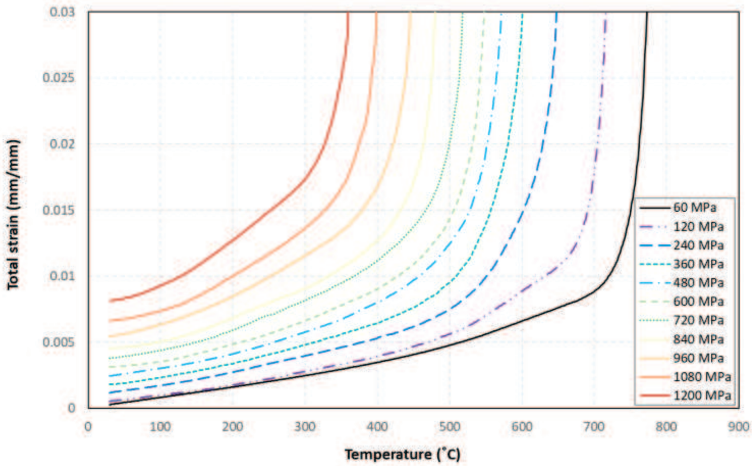


Figure 4. Strain-temperature diagrams at a 10 °C/min heating rate under different stress levels

The total strain ε_{total} measured by the extensometer consists of thermal expansion ε_{th}, mechanical strain ε_{σ}, and creep strain ε_{cr}, as follows:

$$\varepsilon_{total} = \varepsilon_{th} + \varepsilon_{\sigma} + \varepsilon_{cr} \tag{1}$$

To find stress-strain curves, the thermal expansion component of the strain needs to be eliminated. By conducting a transient test under zero load, ε_{th} was measured by the extensometer and subtracted from the total strain to find the summation of mechanical and creep strains; as follows:

$$\varepsilon = \varepsilon_{\sigma} + \varepsilon_{cr} = \varepsilon_{total} - \varepsilon_{th} \tag{2}$$

Then, the stress-strain diagrams including thermal creep effects can be constructed at elevated temperatures using the procedure shown in Figure 5. To this end, at each desired temperature, a vertical line is drawn to cut the strain-temperature curves. Each intersection point corresponds to a pair of stress-strain at that temperature. Then, these pairs of stress-strain can be linearly connected to each other to form a stress-strain curve at that temperature level. In this study, to obtain more stress-strain pairs, horizontal lines were also drawn at various strain levels and stress values corresponding to the temperature level in question were estimated using linear interpolation.

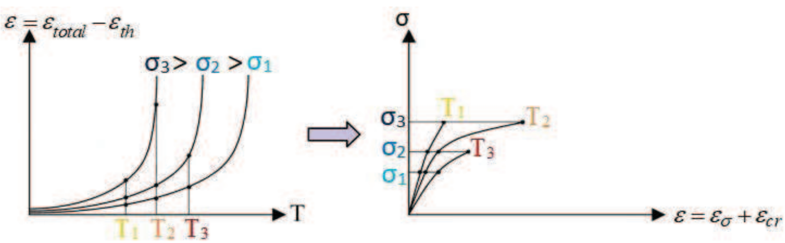


Figure 5. Procedure to find stress-strain curves including creep effects

Figure 6 compares the stress-strain diagrams derived from the transient tests with the ones from the steady-state experiments previously carried out by Azhari et al. (2017) on the same material. Despite the similarities, significant differences are observed between the results of the two testing methods. As seen, the ultimate strength of the material has markedly higher values in the transient tests. For example, at 450°C and 600 °C, the ultimate strengths obtained from the transient tests are, respectively, at least 12% and 14% greater than the ones from the steady-state experiments. The initial slope of the diagrams, however, is lower in the transient tests, meaning that the elastic modulus values calculated based on the steady-state tests are not in the safe side to be utilized for the fire design of Grade 1200 UHSS tubes. This cannot only be attributed to the occurrence of the creep deformations in transient tests, but also to the different loading and heating conditions to which the material is subjected in a transient test and has also been reported in the previous studies (Schneider and Lange 2011) for Grade S460 structural steel.

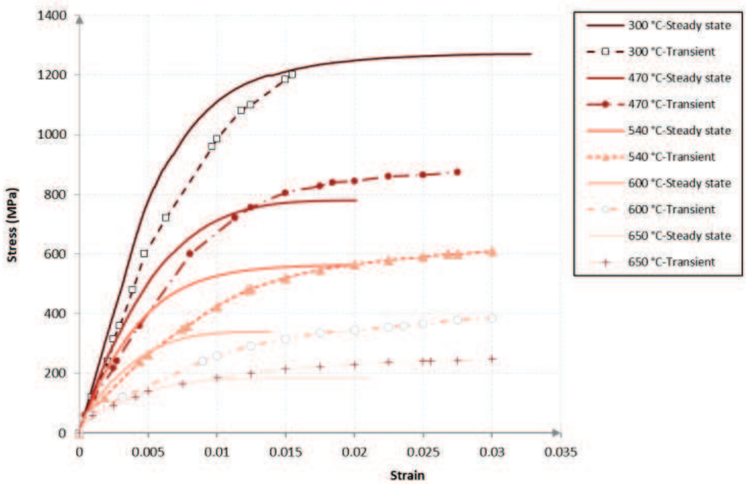


Figure 6. Stress-strain diagrams of Grade 1200 UHSS tubes
at elevated temperatures using steady-state and transient testing methods

4 Summary and Conclusion

High-temperature material behavior of Grade 1200 UHSS tubes was examined. To take thermal creep effects implicitly into account, a transient heating regime was adopted for the experiments, in which the temperature was steadily increased with a rate of 10 °C/min when the specimen was subjected to constant stress levels. Temperature-strain curves obtained from the transient tests which contain mechanical-, thermal- and time-dependent strain fractions were then converted to elevated-temperature stress-strain diagrams. The results clearly differ from those of the steady-state tests previously conducted on the same UHSS tubes without considering the thermal creep effects; in such a way that steady-state test results are not on the safe side in terms of the evaluation of the stiffness of the material.

Acknowledgments

The research work presented in this paper was supported by the Australian Research Council through a Discovery Project (DP150100442) awarded to the third and fourth authors.

References

ASTM Standard E8/E8M, *Standard test methods for tension testing of metallic materials,* ASTM International, West Conshohocken, PA, USA, 2016.

Azhari, F., Heidarpour, A., Zhao, X.-L., and Hutchinson, C., Post-fire mechanical response of ultra-high strength (Grade 1200) steel under high temperatures: Linking thermal stability and microstructure, *Thin-Walled Struct*, 119, 114-125, 2017.

Chen, J., Young, B., and Uy, B., Behavior of high strength structural steel at elevated temperatures, *J. Struct. Eng.*, 132(12), 1948-1954, 2006.

EN 1993-1-2, Eurocode 3 – Design of steel structures, Part 1-2: General rules - Structural fire *design*, CEN, Brussels (Belgium), 2005.

Heidarpour, A., Tofts, N. S., Korayem, A. H., Zhao, X.-L., and Hutchinson, C., *Fire Saf. J.*, 64, 27-35, 2014.

Javidan, F., Heidarpour, A., Zhao, X.-L., and Minkkinen, J., Application of high strength and ultra-high strength steel tubes in long hybrid compressive members: experimental and numerical investigation*, Thin-Walled Struct,* 102, 273-285, 2016.

Kodur, V. K., Aziz, E. M., Effect of temperature on creep in ASTM A572 high-strength low-alloy steels*, Mater. Struct,* 48(6), 1669-1677, 2015.

Maljaars, J., Constitutive Model for Aluminum Alloys Exposed to Fire Conditions, *Metall. Mater. Trans.,* 39(4), 778–789, 2008.

Qiang, X., Bijlaard, F., and. Kolstein, H., Elevated-temperature mechanical properties of high strength structural steel S460N: Experimental study and recommendations for fire-resistance design, *Fire Saf. J.*, 55, 15-21, 2013.

Schneider, R. and Lange, J., Constitutive Equations and Empirical Creep Law of Structural Steel S460 at High Temperatures, *J. Struct. Fire Eng*., 2(3), 217-230, 2011.