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Mechanical properties of cyclically-damaged structural mild steel at elevated temperatures

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HIGHLIGHTS

- Structural grade mild steel samples with cyclically-induced damage are prepared.
- Elevated temperature tensile tests are preformed on pre-damaged samples.
- Mechanical properties of pre-damaged samples are determined from experiment.
- Experimental results are compared to design code expressions.

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ABSTRACT

The mechanical response of a structural element not only depends on the inherent properties of the materials which constitute the element, but also on the history of any loads it had been previously subjected to. An important instance of this is the response of steel structures under post-earthquake fire. This research aims to investigate the potential changes that the mechanical properties of structural grade mild steel experience under such a loading sequence. The experimental results presented in this paper indicate that a prior history of cyclic loading significantly affects the proceeding ductility and strength of grade 300 steel at high temperatures. This implies that any history of cyclic loading should be included in the post-earthquake fire-resistant design of structures.

1. Introduction

In view of the high probability of fires following an earthquake and the extent of the damage associated to them, interest has been shown towards a better understanding of these extreme scenarios. One recent investigation towards this understanding is the work of Tanaka [1] which involves the characterization and categorization of the different types of fire that followed the 2011 Great East Japan Earthquake.

In the context of structural design, fire is generally considered as an independent event regardless whether it was spontaneous or preceded by an earthquake. However, with design codes being directed towards the performance based design philosophy, distinction should be made between ordinary fire and seismic-induced fire. While seismic-induced fire resistance still remains a single design objective, its relevant guidelines and expressions must constitute elements of the fire as well as the preceding seismic loading. Moreover, one can also argue that even if an earthquake is not succeeded by a fire, appropriate guidelines are still necessary to determine the fire resistance capacity of the structure and to assess the need for fire related rehabilitation of a seismically damaged structure.

One aspect of fire related research involves the assessment of temperature distribution and propagation within structural elements. Such an assessment was carried out by Ding and Wang [2] for unprotected connections and by Chlouba and Wald [3] for partially embedded connections. The result of such analyzes is the temperature profile within a structural element. On the other hand, another aspect of fire related research is the assessment of member capacity degradation at elevated temperatures. This degradation is due to the thermo-mechanical phase changes that structural steel exhibits at elevated temperatures. An example of such research is the work of Ding and Wang [4] on different types of composite connections. This work involved transient state experiments, whereby the connection is subjected to a constant load as the temperature is increased. It was concluded that even the most simple connection types are able to develop substantial catenary action before ultimate failure.

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While experiments similar to the one done by Ding and Wang [4] only involve the fire resistance of structural elements, research work has also been carried out on the post-earthquake fire resistance of steel structures and their elements. The post-earthquake fire resistance of plane frames was numerically evaluated by Della Corte et al. [5]. In this work, seismic-induced damage was modeled by decomposing the total damage into a geometrical and a mechanical component. Fire analyzes were then carried out on a structure containing the superposition of these damage components. The work of Zaharia and Pintea [6] is another example of research on post-earthquake fire resistance carried out in the structural scale. This work concluded that the level of seismic damage affects the fire resistance time of a structure. As an example for the post-earthquake fire resistance in the structural element scale, one can point to the work of Pucinotti et al. [7], which investigated the seismic-induced fire resistance of composite welded beam-to-column joints.

Regarding the behavior of structural elements, when comparing the available data on fire resistance as opposed to post-earthquake fire resistance, the former clearly dominates the latter. Similarly, this is also true in the material scale when it comes to the behavior of structural steel at high temperatures and its post-cyclic behavior at high temperatures. However, although not much data is available for the material response of structural grade steel under a post-earthquake fire scenario, extensive effort has been made for the understanding of its behavior at elevated temperatures. For example, the mechanical properties of structural steel at elevated temperatures were investigated by Outinen and Maekelaeinen [8]. This work not only involves the comparison of steady-state and transient-state tests, but also examines the mechanical properties after cool-down. The mechanical properties of high strength structural steel (750 MPa yield strength) at elevated temperatures were compared to those of mild steel (360 MPa yield strength) by Chen et al. [9]. This work concluded that up to temperatures of 500 °C the reduction factors concerning the yield strength and elastic modulus are quite similar for the two steel grades. Various high-temperature relationships expressed in American and European standards were compared with respect to experimental data by Kodur et al. [10]. These included mechanical properties such as strength, as well as thermal properties such as specific heat and thermal conductivity. This work also compared the overall fire resistance predicted by different design codes.

In contrast to the above mentioned investigations on the fire resistance of steel, this paper deals with the post-earthquake fire-resistance of this material. It should be noted that when it comes to the definition of post-earthquake fire, this paper incorporates it in the same sense that is defined by Della Corte et al. [5], i.e. the state of high temperatures succeeding a cyclic loading history at ambient temperature. This is in contrast to another definition used by for example Kumar et al. [11], which involves the state of ambient temperature succeeding a cyclic loading history and a heating–cooldown cycle.

In terms of uncertainty, earthquake and fire are both extremely random events. Therefore, before any attempt to investigate their effects, they have to be converted into a more quantifiable form. For this purpose, in this paper, the post-earthquake fire scenario is replaced by a two-phase loading history that includes a cyclic load at ambient temperature followed by a monotonic tensile load at elevated temperature. Three variables have been proposed for consideration in this program: the amplitude of the cyclic load representing the intensity of the structures oscillations during an earthquake, the number of cycles representing the duration of the oscillations, and the temperature of the tensile phase of loading to represent the action of fire. Mechanical properties are then derived under different combinations of these variables and the results are plotted and compared to the ones obtained without a prior history of cyclic loading.

2. Experimental program

2.1. Test material and specimen

All the specimens used in this study were made of grade 300 mild steel [12], approximately equivalent to ASTM A633A, taken from the flange of 200UB22.3 hot rolled sections [13]. The chemical composition of grade 300 steel is given in Table 1. Preparation of the samples was consistent with the requirements of ASTM E21-92 and ASTM E606-92 [14,15]. The specimen geometry is illustrated in Fig. 1. Actual dimensions of the cross section of the coupon specimens were measured using a micrometer. Both faces of each specimen were ground to give uniform thickness and a smooth finish across the entire surface. Specimens were restrained by means of two 12 mm high strength bolts at each end.

2.2. Test method

There are two major methods of performing elevated temperature tests: transient-state, where the temperature is increased while the sample is under a constant load and steady-state, where the load is increased as the temperature remains constant. While the transient state test method reflects a fire scenario more realistically, the steady-state method is commonly used since it is easier to perform, provides stress–strain curves directly and can be readily used to calibrate models. The steady-state test method is therefore used in this research work.

All samples are subjected to a two-phase load history involving an ambient-temperature cyclic load (phase 1), followed by an elevated temperature monotonic tensile load (phase 2). The test set-up used in this work to perform both phases of loading is shown in Fig. 2. This strain-controlled loading history is illustrated in Fig. 3a as a function of time, whereby $\Delta\varepsilon_c$, N_c and T_m act as the test variables. The outcome of this loading history is the variation of stress with time given in Fig. 3b. Note that in these figures, the dashed line represents the ambient-temperature cyclic phase of the load history, while the solid line represents the elevated temperature monotonic tensile phase. With all of the samples being of the same material and dimensions, the difference between test cases is in their loading histories. Hence, different test cases are denoted in the form of A□C□_T□, where the blank box (□) in front of A, C and T are respectively filled in by the strain amplitude (in %) of the first phase, the number of cycles of the first phase and the temperature (in °C) of the second phase. For instance, A1C3_T020 represents a loading history with 3 cycles of 1% strain amplitude followed by tension at room

Table 1
Chemical composition of grade 300PLUS steel.

C (%)	Si (%)	Mn (%)	S (%)	P (%)
0.25	0.50	1.60	0.040	0.040

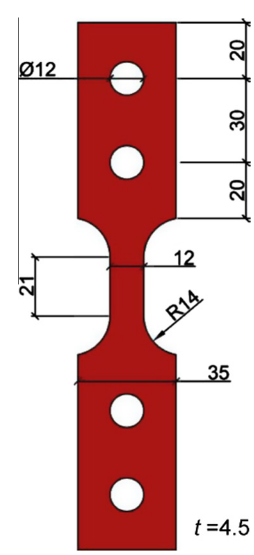

Fig. 1. Sample geometry (in mm).