Construction and Building Materials 122 (2016) 760–771

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Fracture behaviour and microstructural evolution of structural mild steel under the multi-hazard loading of high-strain-rate load followed by elevated temperature

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HIGHLIGHTS

- Post-impact-fire mechanical properties and microstructure evolution of mild steel.
- Various pre-determined deformation levels defined for partially damaged material.
- Test results indicate the coupling effect of strain-rate and subsequent temperature.
- Metallurgical concepts and SEM images used for interpreting the results.
- Pre-deformation history affects the characteristics of steel at high temperatures.

ARTICLE INFO

Article history:
Received 13 July 2015
Received in revised form 25 March 2016
Accepted 23 June 2016

Keywords:
High-strain-rate
Elevated temperature
Coupling effects
Material properties
Microstructure evolution

ABSTRACT

This paper presents the mechanical properties, microstructure evolution and fracture behaviour of structural mild steel subject to the multi-hazard loading scenario of post-impact-fire. Two-phase tensile tests were conducted on mild steel coupons to assess the coupling effect of strain-rate and subsequent temperature at three pre-determined deformation levels. Stress-strain characteristics of pre-damaged steel at different temperatures have been interpreted using well known metallurgical concepts. Scanning Electron Microscopy (SEM) fractographs have been utilized to detect pertinent microstructural alterations. Results indicate that the strength, energy absorption and ductility of steel material at elevated temperatures largely depend on the pre-deformation history of the material caused by high strain rate loading, with this effect dwindling at very high temperatures.

1. Introduction

'Engineering for extremes' has recently gained great attention in the research community. To withstand extremes, which vary from natural hazards such as earthquakes [38,40] to man-made hazards such as impact and blast [30], new techniques are being developed to enhance the performance of protective structures [22,31]. In the event of a bomb blast near a building, or a vehicle collision with a bridge pier, the affected structures not only endure the destructive consequence of high strain-rate impact but are often subject to fire initiating as a result of the explosion or crash. The fire breaks out shortly after the structure has undergone plastic deformation. Little attention was paid to investigating such combined loadings prior to the September 11th, 2001 incident [32]. However, in the aftermath of this event, engineering communities found growing interest in this topic. In recent decades, researchers have proposed numerical approaches [16,29]; or developed analytical methods [21,39] for the analysis of steel frame structures subject to explosive loading followed by fire, to study the effect of explosion-induced deformations and post-explosion fire phenomenon on the performance of structural components or the overall stability of the structure. Their methods have mostly incorporated material models from the literature for individual rate dependency and thermal properties of steel. The accuracy of structural analysis depends strongly on the constitutive model of the material and

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http://dx.doi.org/10.1016/j.conbuildmat.2016.06.122

how accurately it can predict the plastic stress-strain behaviour of materials.

The mechanical properties and fracture behaviour of mild steel are significantly dependent on both the strain rate and the temperature [3]. Numerous studies have been published in the literature which focus on the individual effect of strain rate [27,41,44] and temperature [13,24] on the mechanical properties of steel. Dowling and Harding [17] conducted tensile experiments on mild steel using strain rates varying between $10^{-3}\ \mathrm{s}^{-1}$ and $2000\ \mathrm{s}^{-1}$ and concluded that materials with body-centred cubic (BCC) microstructure (such as mild steel) show a significant strain rate sensitivity. The lower and upper yield stresses, as well as the ultimate tensile strength of mild steel, were found to increase substantially. In contrast, the ultimate tensile strain decreased with increasing strain rate. Poh [33] published experimental results and a new mathematical relationship for representing the stress-strain behaviour of structural steel at elevated temperatures. Chen et al. [12] investigated the mechanical properties of high-strength structural steel and mild structural steel at elevated temperatures using both steady and transient-state test methods and compared the results with the predictions obtained from the American [1], Australian [5], British [10], and European standards [18].

In general, dynamic and thermal loadings not only influence the stress–strain response of structural steel but also the evolution of microstructure [42]. A wealth of literature is available in which the effects of strain rate [19,28,36] and temperature [4,15] on the microstructure of mild steel have been studied. High-strain-rate loading induces irreversible micro-mechanisms of deformation within the material which cannot be neglected when assessing subsequent elevated temperature response of the material. However, studies that have considered the effects of strain rate and temperature on the material plastic deformation (e.g. Refs. [23,25,45]); have generally not considered the consecutive coupling effect of these two parameters. To take into account this sequential loading condition, the tensile deformation response, microstructure evolution and fracture behaviour of high-strain-rate-induced partially damaged mild steel material subject to elevated temperatures are investigated in this study. A series of experiments was carried out in which interrupted high-strain-rate tests were performed on tensile coupons under two different impact rates. Various plastic deformation levels were applied and the deformed material was subsequently exposed to thermal loading in order to analyse the combined influence of loading rate, pre-deformation, and elevated temperature, on the mechanical behaviour of mild steel. Furthermore, microstructural examination of the fracture surfaces is performed using Scanning Electron Microscopy (SEM) images.

2. Methodology

An experimental study aimed to investigate the mechanical properties of high-strain-rate-induced partially damaged structural steel at elevated temperatures has been completed in the Civil Engineering laboratory at Monash University. It enables the influence of initial impact damage on the temperature resistance of mild steel to be evaluated. Detailed descriptions of the test specimens, instrumentation and test procedure have been presented in recent work published by the authors [30]. A summary of the experimental methodology employed to explore the coupled effects of impact loading and thermal loading on structural steel is presented here. Fig. 1 shows an overview of the testing procedure.

Coupon specimens were taken from AS3678-Grade 350 hot-rolled 8 mm mild steel structural plates [6]. The chemical composition is Fe-0.22C-0.55Si-1.7Mn (wt%). The microstructural constituents of the material, consist of pearlite (the layered white structure) in a ferritic (the grey-black structure) matrix, and are illustrated in the SEM image shown in Fig. 2. This is a typical mild steel microstructure.

The test procedure comprised of two consecutive phases. Phase I is a displacement-controlled interrupted **h**igh **s**train **r**ate (HSR) tensile test at ambient temperature. Two nominal strain rates, $1\ \mathrm{s}^{-1}$ and $10\ \mathrm{s}^{-1}$, were used for the tests, henceforth denoted as $HSR_{(\dot{\varepsilon}=1)}$ and $HSR_{(\dot{\varepsilon}=10)}$. Typical strain rates in which materials experience during extreme events of earthquake, impact and blast events are 10^{-2}–1, 1–10^{2} and $>10^{2}\ \mathrm{s}^{-1}$, respectively. The strain rates chosen in this study are to cover the lower limit of the impact rates of strain, i.e. $1\ \mathrm{s}^{-1}$ up to the maximum strain rate achievable by the Instron 8802 servo-hydraulic machine, i.e. $10\ \mathrm{s}^{-1}$.

Tests were interrupted at three predetermined strains to induce different partial deformation. The three chosen damage levels that depict the different stages of the steel fracture process are defined as follows:

- $PD_{=u}$ (Primary damage level): specimen is deformed up to D_u which is the elongation at the point corresponding to its *ultimate tensile strength* (*UTS*).
- $PD_{<u}$ (Lower damage level): terminating elongation is located between the yield point and the ultimate stress point where, although irreversible deformation is induced, the changes in the specimen cross-sectional area are still proportional.
- $PD_{>u}$ (Upper damage level): elongation is past D_u (onset of necking) but is significantly less than the fracture elongation, hence localized deformation and necking has occurred. The upper ($D_{>u}$) and lower ($D_{<u}$) elongation values are approximately evenly spaced from D_u.

As described in [30], the following relationship is used to determine the elongation values for the different damage levels:

$$D_{<u>} = D_u \pm \frac{\alpha}{\log(\dot{\varepsilon}) + 1} \tag{1}$$

in which $D_{<u>}$ is the elongation (in mm corresponding to the $PD_{<u}$ and $PD_{>u}$ damage levels, $\alpha = 2$ (mm/s) and $\dot{\varepsilon}$ is the strain rate (s^{-1}) [30].

The elongation values for each strain rate correspond to the load-displacement curve of the material tested at that particular rate and hence differ for $HSR_{(\dot{\varepsilon}=1)}$ and $HSR_{(\dot{\varepsilon}=10)}$. At the end of Phase I, the partially damaged specimen was taken out of the test machine, the altered cross-sectional area and elongation of the gauge length were measured, and the specimen was subsequently mounted on a load frame with an attached environmental chamber to be tested in Phase II.

In Phase II, a steady-state quasi-static tensile test was conducted on the partially damaged specimen to failure at temperatures ranging from ambient to 600 °C. Tests were carried out in accordance with the standard elevated temperature-testing requirements of AS 2291 (AS2291) inside a temperature controlled environmental chamber (maximum capacity 600 °C) mounted on an Instron loading frame. During the test, the load on the specimen was manually maintained at zero until the temperature was stabilized at the target value. The temperature of the specimen was measured by means of three K-type thermocouples positioned in intimate contact with the surface of the specimen at the top, centre and bottom of the gauge length. Once temperature stabilization was achieved in accordance with the requirements of AS 2291 (AS2291) (for temperatures equal to or less than 600 °C, thermocouple readings are within ±3 °C of target temperature), uniaxial tensile load with a displacement rate of 0.3 mm/min was applied until failure.