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Mechanical properties of partially damaged structural steel induced by high strain rate loading at elevated temperatures – An experimental investigation

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ABSTRACT

In structural engineering practice, understanding the behaviour of steel under extreme loading conditions is essential for accurate prediction of material response when subjected to a combination of severe load scenarios such as collision by heavy objects and a following fire. Hitherto, the combined effects of high strain loading and subsequent elevated temperature have not been widely investigated on the mechanical properties of structural steel. A comprehensive test program is carried out to investigate the post-impact fire properties of Grade 350 steel under well-defined conditions, the results of which are reported in this paper. Coupon specimens have undergone interrupting *high strain rate* (HSR) tensile loading at impact level, controlled locally at different levels of elongation, to account for different deformation states. Three different damage levels are introduced with respect to the displacement corresponding to the ultimate stress (f_u). Subsequently, the partly damaged specimens are subjected to steady-state quasi-static tensile loading to failure at temperatures ranging from ambient to 600 °C. The overall stress–strain relationship, as well as the mechanical properties of pre-damaged steel, are presented at elevated temperatures and compared to those of each individual loading scenario. The test results demonstrate that the effects of these combined actions are profoundly different from those in which the structure is subjected to either high strain rate or thermal loading individually. It is shown that the strength and ductility of mild steel is significantly dependent on the rate of loading, the pre-deformation history and the temperature to which it is subsequently exposed. This necessitates the development of models which take into account the coupled effect of high strain rate and temperature in rational fire analysis and design of steel structures.

1. Introduction

Extreme events such as impact and blast are time-dependent phenomena where a considerable amount of energy is released within a very short period of time. The effect of such extreme actions can be devastating on the performance of civilian structures. With the unfortunate rise of terrorist attacks (such as the 2001 World Trade Centre incident, the 2005 London underground bombings, the 2013 Pakistan bombings, etc.) and road side accidents causing explosions or high speed crashes, the survivability of structures under large dynamic loads and a potential subsequent fire initiating from them have become a major design concern for structural engineers. After the disastrous terrorist attacks of September 11th, 2001 in the USA, the research and engineering communities have given significant attention to investigating the response of structures subject to impact, explosion, and fire.

In recent decades, a growing amount of experimental work has been published aiming to assess the damages caused to structures subject to explosive loadings [1,2]. Steel structures, as one of the most common types of structures, have gained much attention in this regard. Numerous researchers have published their experimental results on the effect of strain rate upon the behaviour of structural steel [3–5] and the mechanical properties

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of mild steel at elevated temperatures [6,7]. Moreover, various analytical and numerical models have been proposed to predict the response of structural steel elements under blast/impact and thermal loading [8–11]. However, there is limited research on the combined effect of these extreme actions, for instance post-impact fire, which is profoundly different from that in which the structure is exposed to either loading [12–14]. The Final Report published in 2005 by the National Construction Safety Team of the National Institute of Standards and Technology (NIST) on the collapse of the World Trade Center Twin Towers reflected that the fire following the aircraft impact and explosion caused catastrophic damage to the structure and led to the progressive collapse of the towers [15]. Most recently Knobloch et al. [16] presented an experimental study on the influence of temperature and especially strain rate on the stress–strain relationship of mild carbon steel with regard to fire conditions. Material tests were performed at elevated temperature under steady-state conditions. Constant levels of strain rate adopted for investigating the strain rate sensitivity ranged from 0.01 s^{-1} to 0.25 s^{-1} for compressive tests, and from 0.333×10^{-5} s^{-1} to 8.33×10^{-5} s^{-1} for tensile tests, covering various scenarios for fire duration. Good correlation was found between the experimental results and reduction factors given in current European and American fire design rules for high strain rates (short fire duration times) but similar conformity was not found for low strain rates (long fire duration times). Well known material models such as the Johnson–Cook model [17], Zener and Hollomon [3] and the Zerilli–Armstrong model [18] used in finite element commercial packages consider the effect of high strain rate while the effect of temperature on the constitutive relations is considered through empirical equations recommended by codes of practice [19,20]. In other words, in the existing constitutive models the coupling effect of strain rate and elevated temperatures are not reflected. High strain rate load induces irreparable plastic deformation to the material which cannot be neglected when assessing the resistance of the material at elevated temperatures. However, hitherto the alterations caused to the mechanical behaviour of structural material at elevated temperatures under the initial impact/blast load have been neglected in the majority of the existing research. Therefore, in order to properly capture the effect of post-impact/explosion fire, the material constants for the constitutive model can be determined using the experimental test data extracted from a fully coupled model.

In this paper a comprehensive experimental investigation under well-defined conditions, which aims to investigate the complex behaviour of high strain rate induced partially damaged structural steel at elevated temperatures, is presented. The experimental results can be used as benchmark data for developing material models which can predict the nonlinear behaviour of structural steel material under high strain rate followed by elevated temperature loading scenarios.

2. Methodology

In this section, the experimental methodology employed to explore the coupled effects of impact loading and thermal loading on structural steel is presented.

2.1. Test specimen

Well established standards are available for tensile testing at quasi-static conditions at ambient temperature [21] and also elevated temperatures [22]. However, with regard to dynamic tensile testing, no published guidelines are available to date for the testing method and specimen dimensions [23]. In this research work, since a high strain rate test is initially performed on the specimen, it is necessary to design the specimen so as to meet the testing requirements of this phase and to compromise the necessary requirements of the subsequent elevated temperatures phase. To the knowledge of the authors, the only document addressing high strain rate test requirements for steel is the publication by the International Iron and Steel Institute [23] which summarises typical specimen geometries used by researchers and testing laboratories, all of which vary significantly in shape and dimensions. The recommendations proposed by the aforementioned document have been adopted for specimen design in this study. As recommend by Borsutzki et al. [23], for high strain rate tests, the length of the deformed zone of the specimen should be sufficiently short and a small radius should be used at the shoulder of the specimen. These conditions require a special geometry of the specimen, which is rather different from the one used at quasi-static strain rates. For this testing program, the specimen geometry is determined so as to ensure higher strain rates and homogeneous deformation of the specimen in the gauge section and more importantly to meet the specific demands of the utilized testing device. Therefore, the specimen shown in Fig. 1 is used. The parallel length (L_P) is determined as per required maximum strain rate. It is worth noting that wherever design has permitted the dimension requirements of AS1391 [21] for flat test pieces are preserved in the geometry. Surface of the specimens are machine ground to ensure a smooth and even thickness of the finished surface and to avoid cracks, notches and other surface defects which can cause stress concentration.

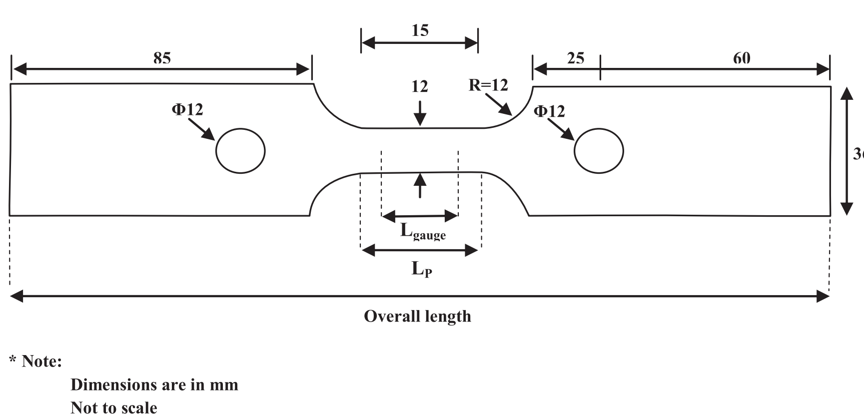

Fig. 1. Test specimen geometry.