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# Strain ageing effect on the temperature dependent mechanical properties of partially damaged structural mild-steel induced by high strain rate loading

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## HIGHLIGHTS

- Strain ageing effect on mechanical properties of partly damaged steel was studied.
- Damage was induced by high strain rate loading followed by elevated temperatures.
- Two-stage experimental program was designed to incorporate strain ageing effect.
- Results have shown the impact of strain ageing on structural steel behaviour.

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## ABSTRACT

This study presents the significant effect of strain ageing on the mechanical response of partially damaged structural steel under extreme loading conditions. Once partial damage occurs in a structure, it takes a while to start the repair process. This lapsed time can substantially affect the strength and ductility of the material. Since the strain ageing effect has not effectively been considered in design guidelines, an understanding of its effect on partly damaged structures is essential. In this paper, a multi-phase loading scenario including high strain rate and quasi-static loadings is applied to the structural mild steel in which partial damage is made to the specimens under high strain rate loading (Phase I). Considering different ageing times ranging from no-age to 7 days, the specimens undergo subsequent quasi-static tensile tests at ambient and elevated temperature (up to 600 °C) until failure (Phase II). Three different damage levels are introduced to examine the damage level effect on strain ageing. It is shown that the variations of ultimate strength and strain values are significantly dependent on ageing time. Presenting a numerical example, the effect of strain ageing on global behaviour of a typical structural component is studied.



## 1. Introduction

The mechanical behaviour of damaged structures has received considerable attention in recent years. The repair of a structure partially damaged by an extreme event may not be initiated immediately. As a result of the time gap (termed 'ageing' in this paper) between the occurrence of the event and commencement of the repair work, the mechanical properties of the partially damaged structural elements may substantially change in terms of strength, ductility, energy absorption, etc.

Partial damage in structures can be caused by various loading conditions. The effect of strain ageing on the residual strength and ductility of the structures partially damaged by high strain rate loading is addressed in this study. To take a typical example, when a structural steel column in a building is partially damaged due to high strain rate loading caused by impact from a vehicle, it may take several days to commence the repair process of the element. The strain ageing phenomenon can substantially alter the mechanical properties of the steel material such that utilizing the primary constitutive material models without incorporating ageing effects may lead to an inaccurate evaluation.

The effect of strain ageing on the mechanical response of structural steel partially damaged by *quasi-static* loading was recently

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investigated by the authors [1] and shown to substantially alter the strength and ductility of the steel [1]. It was demonstrated that this important phenomenon needs to be incorporated into the civil engineering codes of practice. Since the previous work was performed only for damage caused by quasi-static loading, whereas many causes of damage such as vehicular impact, explosions, etc. impart high strain rate damage, there is a need to understand how the damage caused by high strain rate is modified by strain ageing effects.

When steel is deformed, the strain is accomplished at the microstructure scale by the movement of defects, known as 'dislocations'. The strain ageing effect is due to changes in the mobility of the dislocations due to segregation of solute atoms to the dislocations. In the case of steel, the most important solutes from the strain ageing point of view are Carbon and Nitrogen [2]. The dislocation density (the amount of dislocations per unit volume) is an important factor influencing this segregation, and variations in dislocation density are heavily dependent on type of loading applied. Since the pattern of dislocation movement and dislocation density for carbon steel under high strain rate loading are different to that of the same material under quasi-static loading, strain ageing effects may be more significant at even shorter times, or under lower deformation levels, with concomitant effects on the post-loading mechanical response of the steel.

The general mechanical response of steel under high strain rate loading has been comprehensively studied. The behaviour depends on the chemical composition and manufacturing process of the steel. Mechanical properties of mild steel at wide ranges of strain rate have been studied and some existing models were calibrated to describe the behaviour [3]. Knobloch et al. studied the mechanical response of mild steel at elevated temperature and demonstrated that the strain rate has a marked effect on material behaviour [4]. The effect of strain rate and triaxiality on failure of high strength steel was investigated by Anderson et al. [5]. They examined a wide range of strain rate up to 1500 $s^{-1}$ using the Split Hopkinson bar. Mirmomeni et al. [6] investigated the mechanical properties of pre-damaged structural steel induced by high strain rate loading at elevated temperature. They showed that the behaviour under combined action is profoundly different from the behaviour of the material subjected to either high strain rate or thermal loading individually.

Although the behaviour of structural mild steel under extreme loading has been widely studied in the literature, the significant effect of strain ageing on the mechanical properties of steel partially damaged by high strain rate loading has not been addressed. Strain ageing can play a considerable role in designing and rehabilitating of structural elements particularly those which are under extreme loading [7–12]. In general, ageing effects in structural applications can be categorized into two types: short and long term ageing. While long term ageing on concrete and steel structures has been widely investigated in the literature [13,14], the short term ageing effect (occurring on the time scale of hours or a few days) on global behaviour of structures has received more limited attention. Short term ageing can influence the structure after the occurrence of damage and no appropriate design recommendation has been proposed in the prescriptive codes of civil engineering practice to incorporate the effect of short term ageing in assessment of partly damaged steel structures [1].

In this contribution, the effect of damage caused by high strain rate loading on the significance of short term strain ageing effects on mechanical properties of structural mild steel is explored using a two-phase experiment. The experiment includes high strain rate, room temperature deformation followed by quasi-static tests at ambient and elevated temperatures. The effect of ageing on the overall stress-strain curves, ultimate strength, and ultimate strain are investigated.

## 2. Experimental program

### *2.1. Test material and specimen*

The chemical composition of Grade 350 structural mild steel considered in this study can be found in Table 1. This is a typical mild steel consisting of a ferrite/pearlite microstructure (Fig. 1). The white regions in Fig. 1 are the pearlitic aggregates in the microstructure (consisting of fine lamellae of ferrite and cementite ($Fe_3C$)), and the dark regions are the ferrite grains.

The test specimens were taken from AS3678-Grade 350 hot rolled mild steel structural plate which is approximately equivalent to ASTM A572 Gr50 [15].

Samples with geometry indicated in Fig. 2 were machined and both faces of each specimen were ground to give uniform thickness of 7.5 mm and a smooth finish across the entire surface of the specimen.

The room temperature engineering stress-strain curve of the as-received mild steel under quasi-static tensile loading is shown in Fig. 3. The stress-strain curve exhibits a sharp yield point followed by a small Luders plateau and subsequent strain hardening. This mechanical response is typical for mild steel.

### *2.2. Testing procedure*

#### *2.2.1. Inducing partial damage in mild-steel using high-strain rate loading (Phase I)*

The two-phase testing procedure is summarised in Fig. 4. The test specimens were partially damaged to a specific damage level

**Table 1**
Chemical composition of Grade 350 mild steel.

| C | Si | Mn | S | P |
|---|---|---|---|---|
| 0.22% | 0.55% | 1.70% | 0.03% | 0.04% |

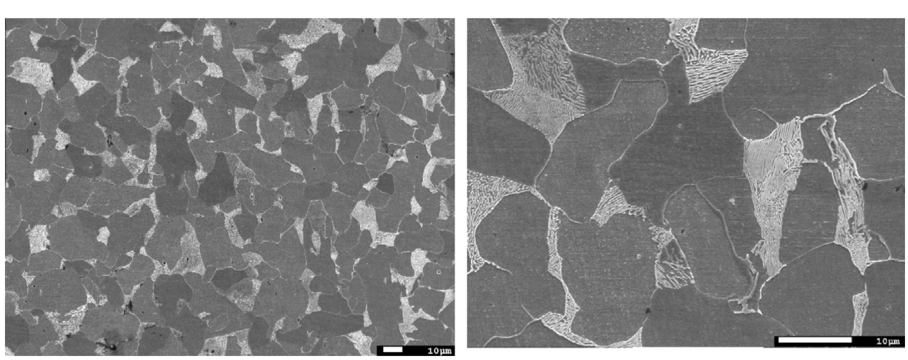


**Fig. 1.** Scanning electron microscopy images of the microstructure of the virgin mild steel.