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Influence of stress concentration and cooling methods on post-fire mechanical behavior of ASTM A36 steels

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HIGHLIGHTS

- Mechanical properties of ASTM A36 steels cooled from high temperatures are studied.
- Air-cooling improves ductility and reduces yield strength of ASTM A36 steels.
- Water-cooling increases tensile strength and reduces ductility of ASTM A36 steels.
- Water-cooling from high temperatures cause formation of hard and brittle martensite.
- Stress triaxiality has strong influence on post-fire mechanical properties of ASTM A36 steels.

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ABSTRACT

This study aims to investigate the influence of stress triaxiality and cooling methods on post-fire mechanical behavior of ASTM A36 steels. To this end, ASTM A36 notched steel specimens are designed to generate a range of stress triaxialities. These specimens are subjected to target temperatures of 500 °C, 600 °C, 700 °C, 800 °C, 900 °C and 1000 °C, and then cooled down to room temperature using air-cooling and water-cooling methods. These specimens are then uniaxially tested to determine their post-fire mechanical properties. Non-linear finite element analysis is conducted using post-fire mechanical properties to obtain stress triaxiality distribution in notched test specimens subjected to different target temperatures and cooling methods. Finally, a Scanning Electron Microscope (SEM) study is conducted on fractured surfaces of representative un-notched and notched test specimens to investigate the influence of high stress triaxiality and cooling methods on fracture initiation and propagation mechanisms. The post-fire mechanical properties of ASTM A36 steels are found to remain almost unaffected when cooled from 600 °C, irrespective of cooling method. ASTM A36 steels experienced up to 14% degradation in ultimate tensile strength and up to 22% increase in fracture strain when air-cooled from temperatures beyond 700 °C. Post-fire ultimate tensile strength is observed to increase by up to 146% whereas fracture strain is observed to decrease by up to 76% when ASTM A36 specimens are water-cooled from high temperatures. High stress triaxiality resulted in up to 37% increase in ultimate tensile strength and up to 74% reduction in ductility of air-cooled specimens. Presence of high stress triaxiality and water-cooling from temperatures beyond 700 °C is observed to significantly increase the ultimate tensile strength (up to 252%) and substantially reduced the ductility (up to 98%) of ASTM A36 steels.

1. Introduction

Structural steels that include mild steels, high strength steels (HSS) and very high strength steels (VHSS) are one of the most popularly used building materials in the United States (US). High thermal conductivity and low specific heat makes structural steels vulnerable to fire accidents [1]. Fire accidents are very common and according to National Fire Protection Agency (NFPA) 2016 report, one structural fire is reported every 63 s in US [2]. In total, 501,500 structural fire accidents were reported in 2015 that accounted for 37% of total fire accidents in US [2]. These structural fires resulted in 2,685 civilian deaths, 13,000 civilian injuries and $10.3 billion in property damages in 2015 alone. Fig. 1 and Fig. 2 illustrate average losses per structural fire in US Dollars and number of structural fire accidents, respectively reported in US between 1978 and 2015. To ensure safety against fire accidents,

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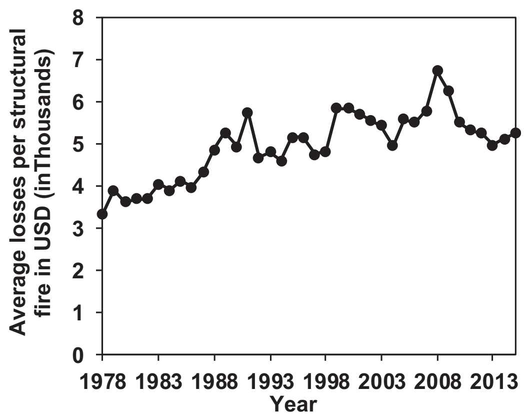

Fig. 1. Average losses per structural fire in USD in the US from 1978 to 2015 [2].

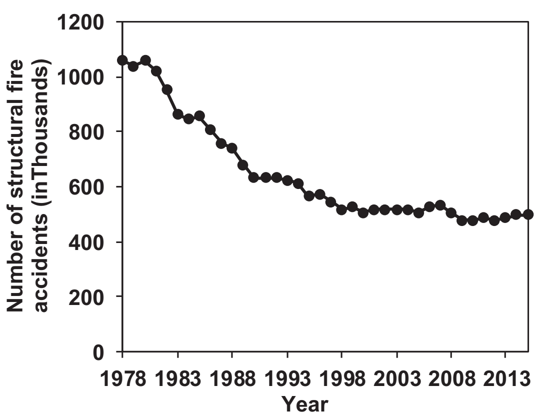

Fig. 2. Number of structural fire accidents reported in the US between 1978 and 2015 [2].

structural steel members must satisfy the fire resistance rating specified in buildings codes. Current design standards such as AISC [3], ASCE [4], BS5950 [5], AS 4100 [6], EC3 [7] and CECS200 [8] have also specified residual factors for estimating elevated temperature mechanical properties of structural steels. As a general rule, the reuse of structural steel after fire exposure is recommended if there is no obvious distortion in the structural members [3,5,9].

After the World Trade Center tragedy, a significant amount of research has been conducted by many researchers to investigate the mechanical properties of various types of structural steels during-fire and post-fire scenarios. Post-fire performance of structural steels is critical in determining the residual capacity and subsequent usability of steel structures, after the fire is extinguished. To this end, post-fire mechanical behavior has been reported for various structural steels that include mild steels (Q235, Q345 [10]), high strength steels (S355J2H [11], Grade 350, Grade 800 [12,13], Q420 [10], Q460 [14], S460NL, S690QL [15], S690RQT [16], Q690 [17,18], ASTM A992 [19], ASTM A572 [20], GLG460, GLG550, GLG650, GLG835 [21]), very high strength steels (S960QL [22], Grade 1200 [12,13]), S690RQT [16], cold-formed steels [23,24], cast steels (G20Mn5N, G20Mn5QT [25]) and stainless steels [26,27]. In these studies, evaluation of post-fire performance of structural steels is achieved by subjecting post-fire steel specimens to uniaxial tension tests. Typical test specimens were prepared and tested in accordance with ASTM E8 [28] or ISO standard (GB/T 228.1-2010 [29]) depending on type of structural steel and the country in which the structural steel is used. For post-fire tests, specimens are first heated to a target temperature and maintained at the target temperature for a certain period of time to achieve uniform temperature throughout the test specimens. Specimens are then cooled down to room temperature using different cooling methods, namely: cooling-in-air (CIA), cooling-in-water (CIW) and cooling-in-blanket (CIB). In the case of CIA, the specimens are cooled by placing them outside the furnace or inside the furnace (with the furnace door kept open) after leaving the specimens at the target temperature for a specified time. In the case of CIW, the specimens are either placed in water or a water-jet is applied to cool down the specimens to room temperature. In the case of CIB, specimens are kept in a ceramic fiber blanket until they are cooled down to room temperature. Residual factors are computed based on one of three cooling methods, as discussed above. Residual factor is defined as ratio of the value of a specific mechanical property after being cooled down from an elevated target temperature to its value at the room temperature. Thus, a high residual factor indicates a lower level of degradation in a mechanical property and vice versa.

The accuracy and reliability of residual factors is vital when estimating the residual capacity of steel structures for post-fire use. Although residual factors for elastic modulus, yield strength, ultimate tensile strength and ductility of various structural steels exist in the literature, the combined influence of stress concentration and cooling method on residual factors is not yet investigated. Stress concentrations are caused by geometric discontinuities like holes, welds, sharp corners, etc. that are commonly observed in steel structures. Stress concentration is quantified by a dimensionless parameter referred to as stress triaxiality (T_σ). Stress triaxiality is defined as the ratio between hydrostatic stress and von-Mises stress. Higher stress triaxiality indicates higher level of stress concentration. High stress triaxialities are found to have an adverse effect on ductility of structural steels [30–33]. With this, the residual factors for ASTM A36 steel for various stress triaxialities and cooling methods are investigated in this paper. The rest of the paper is organized as follows: Section 2 describes the finite element analysis and experimental procedures (heating and cooling procedure and uniaxial tensile testing of test specimens). Section 3 describes test results obtained from uniaxial tensile testing of post-fire specimens and effects of cooling method and stress triaxiality on elastic modulus, yield strength, ultimate tensile strength and ductility of ASTM A36 steel. In addition to this, the influence of stress concentration and cooling method on fracture initiation and propagation mechanisms is also discussed in Section 3. Important conclusions of this study are summarized in Section 4.

2. Experimental procedure

In this section, the details about finite element analysis of test specimens, heating and cooling procedures and uniaxial tension test protocols are provided.

2.1. Finite element analyses of test specimens

In this study, six axisymmetrically notched test specimens are chosen to generate a range of high stress triaxialities. The notched geometries are categorized into three classes based on notch shape, namely: C-notch, U-notch and V-notch. Geometries of these test specimens and dimensions of the notches are provided in Fig. 3 and Table 1, respectively. Non-linear finite element analysis (FEA) is conducted to obtain the distribution of stress triaxialities across the critical cross sections of test specimens. Finite element analyses are conducted using commercial FEA software ABAQUS® [34]. Both notched and un-notched test specimens are modeled using four noded bilinear axisymmetric CAX4 elements that are available in ABAQUS® element library. Geometric non-linearity is considered