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Technical note

Influence of high stress triaxiality on mechanical strength of ASTM A36, ASTM A572 and ASTM A992 steels

Hizb Ullah Sajid, Ravi Kiran *

Dept. of Civil & Env. Engg., North Dakota State University, ND 58105, United States

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ABSTRACT

This study aims at investigating the influence of high stress triaxiality on the yield strength and ultimate tensile strength of commonly used structural steels (ASTM A36, ASTM A572 and ASTM A992). To this end, axisymmetrically notched steel specimens are designed to generate a range of stress triaxialities. Yield strength and ultimate tensile strength of notched steel specimens are then determined using engineering stress-strain curves obtained from uniaxial tensile testing of notched specimens. Yield strength and ultimate tensile strength of all three types of structural steels are found to increase linearly with increase in stress triaxiality of test specimens. Based on experimental and complimentary finite element results, predictive equations are proposed to estimate increased yield strength and ultimate tensile strength as a function of stress triaxiality in structural steels.

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1. Introduction

In service conditions, structural steels are routinely subjected to stress concentrations that arise from geometric discontinuities like holes, sharp corners, welds, etc. that are commonly observed in steel structures. Stress concentration is quantified by a dimensionless parameter referred to as stress triaxiality ($T\sigma$). Stress triaxiality is defined as the ratio between hydrostatic stress and von-Mises stress. Higher stress triaxiality aggravates the growth of microvoids in steel matrix [1], which in turn accelerates ductile fracture initiation in steels [2]. High stress triaxiality thus leads to reduction in ductility of steels [3]. Experimental and numerical studies on high strength low alloy structural steels (ASTM A992) have confirmed the adverse effects of stress triaxiality on ductility of structural steels [4,5]. However, the quantitative relationships between stress triaxiality and yield strength and ultimate tensile strength of structural steels that are important design parameters in structural design [6] are not currently addressed. Past studies conducted on different alloys and stainless steels have reported an increase in tensile strength with an increase in stress concentration [7–9]. Un-anticipated increase in yield strength and ultimate tensile strength of structural steels may lead to unintended consequences in structural systems. For instance, stronger beams cause failure of columns leading to global collapse of the structure (strong beam-weak column). Components like reduced beam sections, seismic fuse components should fail at pre-designed loads to protect the overall integrity and to avoid progressive collapse of structure. It is therefore, important to account for the increased yield strength and ultimate tensile strength due to high triaxiality in the design stage of steel structures [10]. With this objective in mind, the current study aims to establish a quantitative relationship between stress triaxiality, yield strength and ultimate tensile strength of structural steels (at a material level) that are widely used in construction industry. In this study, a mild steel (ASTM A36 [11]) along with two high strength low alloy (HSLA) steels (ASTM A572 [12] and ASTM A992 [13]) are investigated. ASTM A36 and ASTM A992 are predominantly used in construction of steel buildings in the United States whereas ASTM A572 steels are typically used in the construction of bridges [14–16]. ASTM A992 is currently the most common and preferred grade of structural steel used for wide flange shapes in the United States [16,17].

2. Experimental study and finite element modeling

Preliminary finite element analyses are conducted by choosing different geometries of notched tension specimens to generate a range of stress triaxialities. Based on the results obtained from preliminary study, six axisymmetrically notched tension specimens

* Corresponding author.
E-mail addresses: hizbullah.sajid@ndsu.edu (H.U. Sajid), ravi.kiran@ndsu.edu (R. Kiran).

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are selected. These test specimens are classified as CN (circular-notched specimens), UN (U-notched specimens) and VN (V-notched specimens). The reference un-notched test specimens are labelled as SPR (reference un-notched test specimen). Detailed geometric illustrations of the un-notched and notched specimens are provided in Fig. 1. The chemical composition of all the three steels used in this study as specified by the manufacturer are summarized in Table 1. In total, 42 test specimens are tested as a part of this experimental study. These specimens are machined using computer numerically controlled (CNC) lath machine with a tolerance of ± 0.025 mm.

The load-displacement behavior of all the test specimens are obtained by conducting uniaxial tension tests using servo-hydraulic MTS 809 system at a displacement rate of 0.02 mm/s. An Epsilon Model 3542 contact extensometer with 1-inch gage length is used to record the strains. The total load and elongation in the gage length are obtained at a sampling rate of 99 Hz, for both un-notched and notched test specimens. Engineering stress-strain curves of un-notched and notched test specimens are provided in Fig. 2. Near perfect repeatability of load-displacement curves is obtained for all the un-notched and notched test specimens. For the sake of clarity, stress-strain curve of only one representative specimen is provided for each un-notched and notched test specimen. Mechanical properties of test specimens evaluated from experimental stress strain curves are provided in Table 2. Non-linear finite element analysis is conducted to obtain stress triaxiality profiles across critical cross-section at two different loading stages: a) initial stage of loading (corresponding to 1.35 ± 0.5% engineering strain), and b) ultimate load (strain corresponding to maximum stress in engineering stress-strain curve), as shown in Fig. 3. Maximum initial stress triaxiality ($T^i_{\sigma,\max}$) ranges from 0.33 to 1.15. Finite element analyses are conducted using ABAQUS® finite element modeling software. All test specimens are modeled using four noded bilinear axisymmetric CAX4 elements and geometric non-linearity is considered. J_2 plasticity model is used as the constitutive model. For all steels, the true stress strain curves obtained from the corresponding SPR specimens are used as the strain hardening curves in J_2 plasticity model and are provided in Fig. 4. The applied boundary conditions and loading along with some typical finite element meshes used in the vicinity of the notches are provided in Fig. 5.

Table 1
Chemical composition of ASTM A36, ASTM A572, and ASTM A992 structural steels.

Chemical composition (%)	ASTM A36	ASTM A572 Gr. 50	ASTM A992
Carbon (C)	0.1500	0.0500	0.1000
Manganese (Mn)	0.6900	1.3400	0.9300
Phosphorous (P)	0.0180	0.0110	0.0160
Sulphur (S)	0.0040	0.0040	0.0440
Silicon (Si)	0.1800	0.1500	0.1900
Copper (Cu)	0.2400	0.2800	0.2500
Chromium (Cr)	0.1500	0.1900	0.1400
Nickle (Ni)	0.0880	0.1300	0.0900
Molybdenum (Mo)	0.0195	0.0400	0.0200
Vanadium (V)	0.0048	0.0830	0.0010
Titanium (Ti)	0.0012	0.0010	–
Niobium (Nb)	0.0024	0.0030	0.0210
Iron (Fe)	98.4521	97.7180	98.1980

3. Results and discussion

In this section, stress-strain curves, yield strength (σ_y) and ultimate tensile strength (σ_u) obtained from uniaxial tensile tests are discussed. Using engineering stress-strain curves, yield strength of each test specimen is determined based on 0.2% strain offset method [18]. The maximum engineering stress is taken as the ultimate tensile strength of steel. As observed in Fig. 2, stress-strain curves of notched specimens are characterized by significant reduction in ductility and increase in ultimate tensile strength as compared to un-notched specimens, for all three types of steels. A well-defined yield plateau is observed in un-notched specimens which diminishes in case of notched specimens with high stress triaxiality. It is observed that all notched specimens exhibited substantial increase in both yield strength and ultimate tensile strength as compared to un-notched steel specimens. Among notched steel specimens, highest yield strength and ultimate tensile strength is exhibited by specimens with highest average initial and average ultimate triaxialities (UN1 and VN1), respectively. In

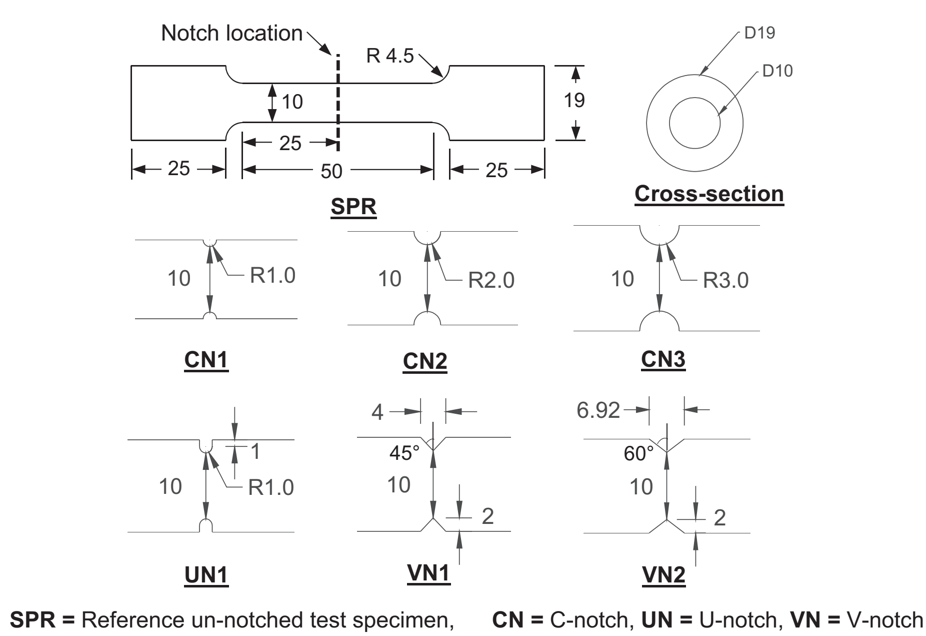

Fig. 1. Geometric details of axisymmetric test specimens (all dimensions are in mm.).

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