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Prediction of the fracture performance of defect-free steel bars for civil engineering applications using finite element simulation

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HIGHLIGHTS

- ▶ Phenomenological shear failure model predicts fracture performance of bar.
- ▶ The optimum element size to predict the fracture performance of bar is 0.0625 mm^3.
- ▶ Element orientations influence bars fracture performance prediction.
- ▶ 2:1 Element aspect ratio is required for accurate bar's fracture shape prediction.

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ABSTRACT

The size of bars for civil engineering applications makes it impossible for traditional classical fracture mechanics to be employed to predict their fracture performance. This paper presents finite element simulations of the fracture performance of bars conducted with micromechanical fracture mechanics approach. Appropriate element size, orientation and aspect ratio were found to be essential for predicting the fracture shape of bars. It is demonstrated that finite element simulation with micromechanical-based phenomenological shear failure model can predict the fracture performance of defect-free bars and thus serves as an alternative to using non-standardised classical fracture mechanics specimens for bars' fracture performance prediction.

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1. Introduction

There is a need for an understanding of the fracture performance of steel wires and bars used for pre-stressing concrete structures, and for construction of suspension bridges, among other applications in civil engineering. This need arises because the fracture performance of steel wires and bars for civil engineering application is a major concern in civil engineering construction and maintenance wire and/or bar reinforced structures [1]. Carbon steel wires (usually 2.5–8 mm in size) and bars (10–32 mm) may contain cracks introduced into them from the production line by certain production processes such as rolling and drawing [2]. During the service life of wires and bars, cracks could also be introduced into them by mechanisms such as fatigue, corrosion (such as stress corrosion cracking), corrosion-fatigue, hydrogen induced cracking or hydrogen-induced stress corrosion cracking (a combination of both stress corrosion cracking and hydrogen-induced cracking) [2]. While good quality control and quality assurance could eliminate cracking of pre-service wires and bars, wires and bars in operations may not be completely defect-free or crack-free.

The size of wires and bars (particularly small bars) used for civil engineering applications makes it impossible for traditional classical fracture mechanics to be employed to predict their fracture performance. This explains why to date, the published work on the failure analysis and fracture performance of wires and bars (up to 12 mm in size), such as the research conducted by [3] on bridge cable wires, and by [4,5] on concrete pre-stressing wires were based on experimental fracture mechanics work conducted with non-standardised traditional fracture mechanics specimens as standard classical fracture mechanics test specimens could not be manufactured from the wires and bars owing to their sizes. The traditional classical fracture mechanics approach requires large specimen size. The specimen size dependence of the traditional classical fracture mechanics approach and the concern about the applicability of the traditional fracture mechanics in civil structures has necessitated the need to employ micromechanical

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fracture approaches that explicitly simulate micromechanical material processes which characterises fracture in civil structures [6].

Micromechanics fracture approach serve as alternatives to the traditional classical fracture mechanics when standard fracture mechanics specimens cannot be obtained and when a safe use of the classical fracture mechanics concepts cannot be insured [7]. Micromechanics fracture approach guarantees the transferability from specimens to structures over a wide range of sizes and geometries and is suitable for problems involving ductile fracture of crack-free bodies as it does not require pre-cracked specimen needed for classical fracture mechanics approach [8]. The micromechanical-based phenomenological fracture models are based on the principle that ductile fracture occurs when a weighted measure of the accumulated plastic strain, such as the equivalent plastic strain reaches a critical value [9,10].

The need to employ simulation-based investigation of fracture of civil engineering structures which reduces the need for costly large-scale testing, allows for parametric studies which can examine situations which may not be feasible to test and provides researchers with a tool to develop insights into localised effects that trigger fracture has been emphasised recently by [6]. To date, no finite element (FE) simulation to predict the fracture performance of bars (particularly small bars of up to 12 mm in size) for civil engineering applications has been published as the published work on the fracture performance (estimation of fracture load or stress, displacement at fracture or strain, failure analysis and general fracture behaviour) of wires and bars for civil engineering applications were based on experimental work.

In this paper, the fracture performance of a typical defect-free (having passed the defect screening test conducted with the inline electromagnetic defect detection system) carbon steel bar used for civil engineering applications subjected to tensile loading is numerically studied using finite element simulation. The FE analysis covered the prediction of failure associated with the onset of damage due to plastic instability at the ultimate load point, the prediction of fracture initiation parameters (fracture load and displacement at fracture) and the prediction of the final fracture phenomenon of the bars. Three dimensional simulations were conducted using the isotropic elastic–plastic model combined with the phenomenological shear damage and fracture model inbuilt in the Abaqus 6.9-1 finite element code material library. The details of the laboratory test and the FE models and simulation procedures employed for the numerical tensile tests conducted are presented in Sections 2 and 3 respectively. The results of the laboratory and numerical simulations are presented in Section 4 and are discussed in Section 5. The conclusions drawn are presented in Section 6.

2. Experimental

Laboratory tensile tests were conducted on 170 mm long, 50 mm gauge length un-machined full cross section bar specimens recommended by [11,12] shown in Fig. 1. The tests were conducted at an ambient temperature of 20 °C and a relative humidity of 38%. Two bar sizes with 12 mm × 5 mm and 12 mm × 7 mm cross-sectional dimensions were tested with an Instron universal testing machine (IX 4505) fitted with wedge grips and an Instron 2518 series load cell with a maximum static capacity of ±100 kN. The displacement was measured using an Instron 2630–112 clip-on strain gauge extensometer with a 50 mm gauge length which ensured that only the displacement within the 50 mm gauge length of the bar specimens was measured. The tensile tests were conducted at a cross head speed of 5 mm/min.

3. Finite element tensile testing simulation

Three dimensional finite element (FE) analysis of the tensile failure (damage behaviour and fracture performance) of the bar specimens was conducted using FE simulation of the tensile testing of the bar specimens. The tensile failure simulation consists of the prediction of the undamaged response of the bar using the isotropic elastic–plastic model and the prediction of the failure (damage and fracture) behaviours of the bars using the shear damage and fracture model in Abaqus 6.9-1 finite element code materials library. Details of these two models are as follows:

3.1. Isotropic elastic–plastic model

The isotropic elastic–plastic model in Abaqus is based on a linear isotropic elasticity (valid for small elastic strains) and a plasticity theory in which the elasticity is not affected by the inelastic (plastic) deformation, (i.e. the Young's modulus of a metal specimen is not changed by loading it beyond yield, until the specimen is very close to failure) [13]. The model is suitable for modelling involving large plastic straining of metals with a yield surface that changes size uniformly in all directions, such that the yield stress increases (or decreases) in all stress directions with plastic straining (large deformation) [13,14]. The model predicts the undamaged material response which consists of the linear elastic behaviour, the yielding behaviour and the plastic response. The material input (modelling) parameters for the model are the density, Young's modulus, Poisson's ratio, and the post yield true plastic stress and strain. The elastic aspect of the model is defined in terms of its volumetric and deviatoric components given in Eqs. (1) and (2) respectively obtained from [13]. The plastic aspect of the model is based on: a von Mises yield surface, a uniaxial-stress plastic-strain strain-rate relationship and an isotropic hardening with a yield function f, given in Eq. (3). The flow rule for the model is given in Eq. (4) obtained from [13].

$$p = -K\varepsilon_{vol} \tag{1}$$

$$S = 2Ge^{el} \tag{2}$$

$$f = q = \sqrt{\frac{3}{2}S : S} \tag{3}$$

$$de^{pl} = d\bar{e}^{pl}n \tag{4}$$

where p is the equivalent pressure stress, ε_{vol} is the volume strain, S is the deviatoric stress, e^{el} is the deviatoric elastic strain, q is the von Mises equivalent stress, e^{pl} is the deviatoric plastic strain, $\bar{e}^{pl}$ is the equivalent plastic strain, $n = \frac{3}{2}\frac{S}{q}$, K is the bulk modulus and G is the shear modulus. K and G are calculated from the Young's modulus, E, and Poisson's ratio, v, of the material.

3.2. Shear failure model

The shear fracture is one of the two main mechanisms (the other being the ductile fracture due to the nucleation, growth, and coalescence of voids) by which ductile metals fracture [13]. The shear damage and fracture criterion is a phenomenological

Fig. 1. Un-machined full size bar specimen.

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