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# Identification of Micromechanical Fracture Model for Predicting Fracture Performance of Steel Wires for Civil Engineering Applications

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***Abstract*****—**The fracture performance of steel wires for civil engineering applications remains a major concern in civil engineering construction and maintenance of wire reinforced structures. The need to employ approaches that simulate micromechanical material processes which characterizes fracture in civil structures has been emphasized recently in the literature. However, choosing from the numerous micromechanics-based fracture models, and identifying their applicability and reliability remains an issue that still needs to be addressed in a greater depth. Laboratory tensile testing and finite element tensile testing simulations with the shear, ductile and Gurson-Tvergaard-Needleman's micromechanics-based models conducted in this work reveal that the shear fracture model is an appropriate fracture model to predict the fracture performance of steel wires used for civil engineering applications. The need to consider the capability of the micromechanics-based fracture model to predict the "cup and cone" fracture exhibited by the wire in choosing the appropriate fracture model is demonstrated.

***Keywords*****—**Fracture performance, FE simulation, Shear fracture model, Ductile fracture model, Gurson-Tvergaard-Needleman fracture model, Wires.

## I. Introduction

STEEL wires are used in civil engineering as pres-stressing steel wires and as suspension and/or cable stayed bridge wires. The fracture performance (prediction of fracture load/stress, fracture strain/displacement at fracture, fracture initiation point, fracture propagation and fracture path or sequence) of steel wires is a major concern in civil engineering construction and maintenance of civil engineering structures where wires provide the required structural reinforcement [1]. Recent research on the failure analysis of wires, such as the research conducted by [2] on bridge cable wires, and by [3] and [4] on concrete pre-stressing wires were based on experimental classical fracture mechanics approach using non-standardized fracture mechanics specimens. Non-standardized fracture mechanics specimens were used because the pre-stressing and suspended bridge wires are not large enough for standard traditional fracture mechanics test specimens to be manufactured from the wires [2]-[4]. The large specimen size requirement by 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 approaches that explicitly simulate micromechanical material processes which characterizes fracture in civil structures [5].

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Micromechanics-based (micromechanical and phenomenological) fracture mechanics models 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 [6]. 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 the pre-cracked specimen needed for classical fracture mechanics tests [7].

Micromechanical fracture modeling involves the modeling of void nucleation and growth, and is based on the assumption that ductile fracture occurs when the void volume fraction reaches a critical level; hence, such models involve modeling of void nucleation and growth [8]. Phenomenological models are alternatives to micromechanical based models as they predict ductile fracture without modeling void nucleation and growth [8]. Phenomenological models are based on the assumption that ductile fracture occurs when a weighted measure of the accumulated plastic strain, such as the equivalent plastic strain, reaches a critical value [8].

There are many micromechanical and phenomenological constitutive models for ductile damage and fracture prediction. However, choosing from the numerous micromechanical and phenomenological models, and identifying their applicability and reliability remains an issue that still needs to be addressed in greater depth [9]. This is because using an inappropriate model may result in unreliable or inappropriate ductile fracture predictions, which has been a problematic issue in industrial applications of ductile failure models [9]. Also the need to identify the ductile fracture model which is able to predict ductile fracture in a way that is to the largest extent in agreement with actual phenomena in a material has been stressed by [10]. However, in most published literature such as [7]-[11], the appropriateness (applicability and reliability) of many ductile fracture models to describe the fracture behavior of materials are based on the ability of such models to predict force-displacement/reduction in area curves that agree with the experimental curve up to the fracture initiation point. The simulation techniques used to obtain such curves have also been adjudged to be appropriate.

In this work, the identification of the appropriate ductile fracture model for a typical high strength steel wires used in structural engineering applications from three micromechanics-based models that are inbuilt in Abaqus 6.9-1 finite element (FE) code was conducted by comparing the force-displacement curves and the fracture shapes obtained from experimental tensile testing and finite element (FE) tensile testing simulations.

The isotropic elastic-plasticity model in Abaqus is based on linear isotropic elasticity theory and a uniaxial-stress, plastic-strain strain-rate relationship [12]. The shear failure criterion is a phenomenological model for predicting the onset of damage due to shear bands. Applied stress causes shear band formation and localization, leading to the formation of cracks within the shear bands and eventual failure [13]. The ductile damage criterion is a phenomenological model for predicting the onset of damage by micro-void nucleation, void growth and void coalescence [13]. Micro-void nucleation could be as a result of micro-cracking of particles and/or fracture or decohesion of second phase inclusions. Plastic straining causes the nucleated voids to grow or enlarge, leading to localization of plastic flow between the enlarged voids and eventual ductile tearing of the ligaments between the enlarged voids [14]. The porous metal plasticity (PMP) model is a micromechanical model used in modeling damage and failure of voided metals. It is based on the Gurson's porous metal plasticity theory which is based on the assumption that the yield stress of the fully dense matrix material is a function of the equivalent plastic strain in the matrix. It predicts failure by nucleation of new voids, and growth and coalescence of both existing voids and nucleated voids, with final failure occurring by ductile crack propagation (ductile tearing). Interested readers are referred to [12], [13] and [15] for the details of the mathematical equations for the isotropic elastic-plasticity model, shear and ductile failure models and the porous metal plasticity model respectively.

## II. EXPERIMENTAL

The details of the experimental measurements and FE simulations are presented in this section.

### *A. Laboratory Tensile Testing*

Un-machined full cross section specimens of 12mmx5mm and 12mmx7mm wires sizes recommended by [16] and [17] were tested with an Instron universal testing machine (IX 4505) with a maximum static capacity of ±100kN. The Instron universal testing machine was fitted with an Instron 2518 series load cell and the displacement was measured using an Instron 2630-112 clip-on strain gauge extensometer with a 50 mm gauge length.

### *B. Finite Element Tensile Testing Simulation*

The three dimensional FE simulation of the tensile testing of the wire specimens was conducted using the in-built isotropic elastic-plastic model combined with the ductile, shear and porous metal plasticity fracture models in Abaqus 6.9-1 finite element code. The FE simulation was conducted by fixing the left hand end of the full three dimensional model of the wire and subjecting the right hand end, which is free to move only in the direction of the tensile load to a longitudinal displacement as shown in Fig. 1. The FE tensile testing simulation was conducted for the 12mm x 5mm and 12mm x 7mm wire sizes.

The elements at the middle region of the model of the wire was refined and meshed with 0.25x0.25x1mm C3D8R elements (8-node hexahedral linear brick reduced integration elements with hourglass control) as shown in Fig. 1. 0.25x0.25x1mm element size with the 1mm dimension in the direction of the length of the specimen was established through mesh convergence study to be the optimum element size needed to effectively capture the amplified stress at the middle of the specimen during necking and provide sufficient numbers of elements across the thickness and width of the model for the simulation to predict the experimental fracture shape of the wire. The outer regions of the model of the wires specimen were meshed with 1mmx1mmx1mm C3D8R elements.

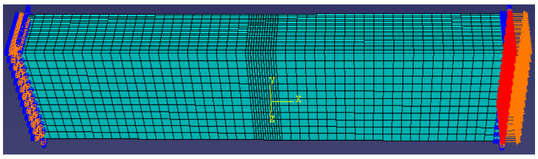


Fig. 1 Meshed model of wire specimen

The shear damage and fracture modeling parameters used for the FE simulations are fracture strain of 0.3451, shear stress ratio of 12.5, strain rate of 0.000125$s^{-1}$ and a material parameter $K_s$ of 0.3. The ductile damage and fracture modeling parameters used for the FE simulations are fracture strain of 36.5618, stress triaxaility of 3.66663 and strain rate of 0.00011$s^{-1}$. The porous metal plasticity modeling parameters used for the FE simulations are void volume fraction ($f_N$ ) of 0.004, critical void volume fraction at failure ($f_C$) of 0.004, total void volume fraction at failure ($f_F$) of 0.06, coefficients of the void volume fraction $q_1$ and $q_2$ of 1.5 and 1.0 respectively, coefficient of pressure term $q_3$ of 2.25, average nucleation strain $\varepsilon_N$ of 0.3 and standard deviation $S_N$ of 0.1. The values of these modeling parameters are the calibrated values, which were obtained through a phenomenological fitting process. They represent the values of the modeling parameters at which the FE predicted force-displacement curves fit with the experimental force-displacement curves. The phenomenological fitting procedure involves keeping some parameters constant and varying others during numerical simulations until the simulation results fit the experimental data, usually up to the fracture initiation point [7].

## III. Results

The fractured laboratory specimens of the two wire sizes which exhibit a "cup and cone" fracture (flat fracture at the center and slant fracture at the outer regions of the specimen) are shown in Fig. 2. The normalized experimental force-displacement curves and the normalized force-displacement curves predicted by the FE simulations conducted with the shear, ductile and porous metal plasticity failure models for the 12mmx5mm and 12mmx7mm wire sizes are shown in Figs. 3 and 4 respectively. The fracture shapes predicted by the simulations conducted with the three ductile fracture models for the two wire sizes are the same. Consequently, only the fracture shapes for the 12mmx5mm wire models predicted by the simulation conducted with the porous metal plasticity, ductile and shear failure models, and the fracture shape predicted by the simulation conducted with the shear failure model for the 12mmx7mm wire model are shown in Figs. 5 (a), (b), (c), and (d) respectively.


(a) 12mmx5mm wire


(b) 12mmx7mm wire

Fig. 2 Cup and cone fracture shape exhibited by fractured experimental wire specimens

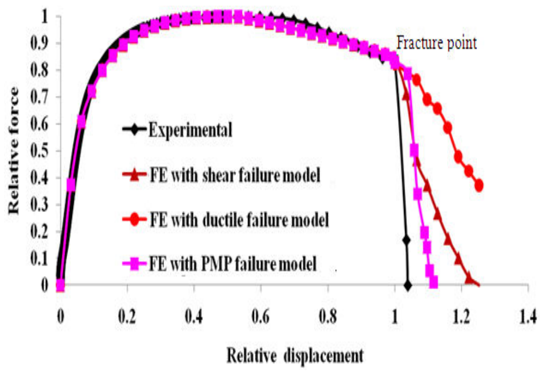



Fig. 3 Normalized experimental and FE force-displacement curves for12mmx5mm wire

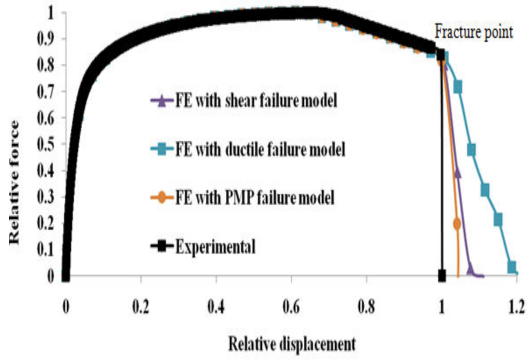
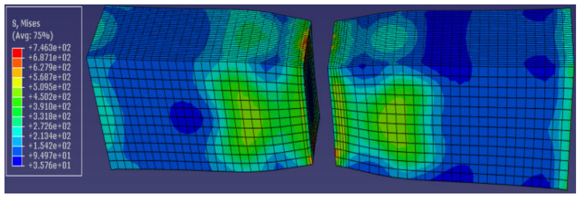
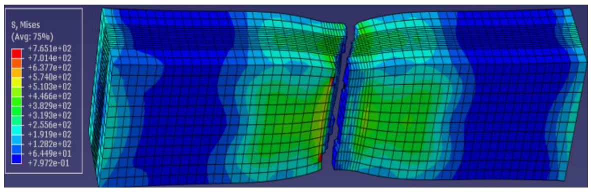


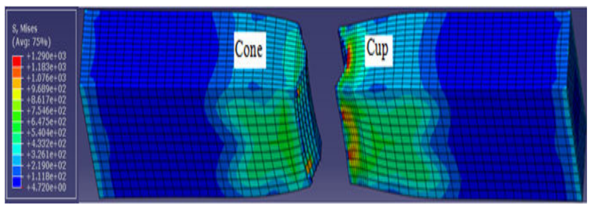

Fig. 4 Normalized experimental and FE force-displacement curves for12mmx7mm wire



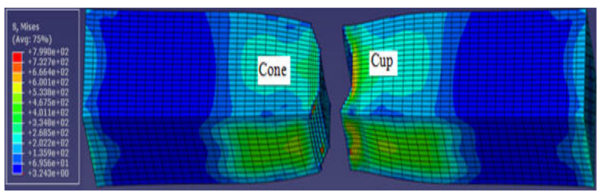
(a) Fracture shape predicted by FE simulation with porous metal plasticity fracture criterion



(b) Fracture shape predicted by FE simulation with ductile fracture criterion




(c) Fracture shape predicted by FE simulation with shear fracture criterion for 12mmx5mm wire




(d) Fracture shape predicted by FE simulation with shear fracture criterion for 12mmx7mm wire

Fig. 5 Fracture shapes predicted by FE simulations conducted with the three ductile fracture models

## IV. Discussion

As shown in Figs. 3 and 4, there is no significant difference in the force-displacement curves predicted by the simulations conducted with the shear, ductile and porous metal plasticity failure models up to the fracture initiation point. This result indicates that the three ductile failure models are able to predict the tensile response of the wire up to the fracture initiation point. On the basis of adjudging the ductile fracture models' appropriateness (applicability and reliability) by their ability to predict the force-displacement curve that agrees with the experimental curve as published by [7]-[11] among others, any of the shear, ductile and porous metal plasticity failure models considered in this work can be adjudged as an appropriate fracture model for the wire. However, as shown in Figs. 5 (c) and (d), for the two wire sizes considered, only the simulation conducted with the shear failure model predicted the "cup and cone" failure exhibited by the fractured experimental wire specimens shown in Figs. 2 (a) and (b). The simulations conducted with the porous metal plasticity and the ductile failure criteria predicted flat and slant fracture as shown in Figs. 5 (a) and (b) respectively.

The ability of the shear fracture model alone to predict the "cup and cone" fracture exhibited by the fractured experimental specimen indicates that out of the three fracture models considered in this work, only the shear fracture model can be adjudged as the appropriate fracture model to predict the fracture performance of the wire. The inability of the ductile and porous metal plasticity fracture models to predict the flat to slant fracture propagation, which represents the fracture path or sequence associated with the cup and cone fracture behavior exhibited by the experimental fractured wire specimens does not makes the ductile and porous metal plasticity fracture models appropriate fracture models suitable for the prediction of the fracture performance of the wire.

## V. Conclusions

This study has established that it is not sufficient to choose any of the shear, the ductile or the porous metal plasticity micromechanics-based fracture models as an appropriate fracture model to predict the fracture performance of wires for civil engineering applications on the basis of a good agreement between the experimental and FE predicted force-displacement curve alone as is generally practiced. The need to consider the capability of the micromechanics based fracture model to predict the fracture sequence or path and the actual fracture shape exhibited by the experimental fractured wire specimens in choosing the appropriate fracture model has been demonstrated. Out of the shear, the ductile and the porous metal plasticity ductile failure models in-built in the Abaqus finite element code considered in this work, the shear failure model has been identified as the appropriate fracture model that is able to predict the “cup and cone” fracture shape or behavior exhibited by the fractured experimental wire specimens. Thus, FE tensile testing simulation with the phenomenological shear fracture model can thus be used to predict the fracture performance of wires for structural engineering applications.

It is hoped that, the use of FE tensile testing simulation with the phenomenological shear fracture model would be employed by engineers to predict the fracture performance of wires for civil engineering applications, which will allay the concerns on the fracture performance of the wires that are associated with the use of the traditional classical fracture mechanics approach for the prediction of the fracture performance of wires for civil engineering applications.

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