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Simulation of ductile fracture in welded tubular connections using a simplified damage plasticity model considering the effect of stress triaxiality and Lode angle

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ABSTRACT

In the experiment of the welded CHS–RHS X-joint, ductile fracture initiated on the chord near the saddle position along the brace-to-chord intersection which led to punching shear failure mode. The initiation and extension of the ductile fracture reduces the punching shear resistance of the remaining intact material. In order to estimate the accurate strength and the failure mode of tubular connections, this paper proposes a new fracture model by extending the existing damage-mechanics based models to predict the ductile fracture failure in tubular connections. The proposed model considers not only the effect of the stress triaxiality but also the effect of the Lode angle on the fracture strain, so as to make an enhanced estimation on the "shear fracture mode". To facilitate its engineering application, this paper proposes a simplified method to calibrate the material parameters solely from experimental results of common coupon tests. Besides, to examine the engineering application of the proposed fracture model to other types of welded tubular connections, this paper applies the proposed fracture model in analyzing the fracture failure in a welded CHS-plate X-joint, and further two I-beam-to-tubular-column connections reported by previous researchers. The numerical simulation predicts accurately the actual failure sequence observed in the experiment.

1. Introduction

Extensive experimental evidences [1–4] reveal that ductile fracture has emerged as a predominant failure mode in hollow section connections under tension. However, engineering assessments of fracture failures in welded tubular connections face a number of fundamental barriers, including the scalability of the material fracture toughness to the fracture resistance in large-scale structural connections and the representation of the fracture failure under varying levels of triaxial and deviatoric stresses. The damage-mechanics based numerical methods, rendering convenient means to describe the material failure in a medium-to-large scale welded connection, often require detailed calibrations of material parameters from carefully instrumented experimental studies. However, experimental investigations, imbued with costly preparations and intricate facilities for large-scale tubular connections, imposes practical constraints in the routine engineering assessment. Hence, a properly calibrated simplified numerical model based on the damage mechanics becomes essential to predict the ductile fracture failure frequently observed in hollow section connections.

The ductile fracture in steel originates from the nucleation, growth and coalescence of microscopic voids, as described by the micromechanically based constitutive models [5,6]. Phenomenological representations of ductile fracture often consider the fracture initiation and its subsequent failure as a result of the accumulation of ductile plastic damage [7]. However, direct measurement of the material damage remains infeasible. The damage-mechanics based models aim, instead, to develop a relationship between the damage variable and some measurable engineering parameters, in order to utilize the cumulative damage to predict the onset of fracture. Previous researchers [8–10] have proposed various fracture models (VGM model and the extended models) to predict the fracture initiation. These fracture models have addressed the influence of stress triaxiality (also known as the constraint effect) on the fracture strain in ductile solids. They have demonstrated the apparent enhancement in the ductility of the steel material in the presence of a surrounding compressive pressure. Nevertheless, these fracture models have not addressed the effect of shear or deviatoric stresses, quantified by the Lode angle of the principal stresses, on the fracture strain. A large number of experimental investigations [11–13] have demonstrated significant difference in the fracture strains in non-axisymmetric loading conditions and those in the axisymmetric loading condition. For instance, Clausing [11] reported that the fracture strain in a plane strain condition is lower than that in an axisymmetric condition.

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Additional evidences [12,13] have shown that the simple shear fracture strain can be less than the simple tension fracture strain. Numerical analyses based on the micromechanical constitutive models have also elucidated the clear dependence of the void growth and void coalescence process on the Lode angle of the principal stresses [14,15].

According to the previous experimental studies conducted in Tongji University [16–20], the fracture failure in welded tubular connections are usually characterized by the fracture in the welds and the punching shear fracture in the chord (main) member. The Fracture models without considering the Lode angle effect, taking the VGM model and the extended models for example, have been widely used in the fracture prediction of steel structures [21–23]. They provide good prediction of the fracture strain for simple structural geometries, e.g., tensile bars, I-beams etc., in which the fracture failure is primarily "tensile fracture mode" and the Lode angle effect remains negligible. However, the VGM model is not suitable for tubular connections, due to the significant Lode angle effect caused by the "shear fracture mode". For such connections, the VGM model often overestimates the fracture strain. Therefore, the VGM model should be modified to enhance its prediction on the fracture strain for tubular connections.

The historical development of the damage mechanics models have incorporated the effect of the Lode angle. In 1980, Wilkins [13] proposed a fracture criterion for ductile fracture under torsion-tension conditions. Recently, Xue [24] proposed a damage plasticity model, which defines a fracture strain envelope in the principal stress space considering the effects of both the mean stress and the Lode angle of the principal stresses. The internal "damage" variable, which describes the material deterioration, is measured at the current load level with respect to the fracture strain envelope, and is calculated by integrating a weight function with respect to the plastic strain increment. The fracture strain envelope in this model requires calibration of quite a number of material parameters against multiple laboratory tension tests. For instance, the Xue model entails three key functions: (1) the pressure sensitivity function, (2) the Lode angle dependence function, and (3) the damage accumulation rule. The determination of the pressure sensitivity function and the Lode angle dependence function remains approximate in nature, since the direct calibration is infeasible due to the lack of an experimental approach to measure the ductile fracture strain envelope at a constant pressure or a constant Lode angle. To solve this problem, Xue [25] has subsequently assumed a Tresca failure condition, i.e., the maximum shear stress failure condition, and a Drucker–Prager type linear pressure sensitivity relationship for the fracture strain envelope in the principal stress space. These assumptions lead to the development of a stress-based fracture strain envelope (denoted as the modified Xue model in the text below) [25]. The modified Xue model presents a fracture stress envelope and derives the fracture strain envelope from the stress–strain relationship. The modified Xue model reduces significantly the calibration effort required in both the Lode angle dependence function and the pressure sensitivity function. The reference strain, i.e., the uniaxial tensile failure strain without a confining pressure, and the stress–strain relationship become the essential experimental data required in the modified Xue model.

Despite the pronounced improvement rendered by the modified Xue model in facilitating its engineering applications, the detailed parameter calibration necessitates complicated numerical iterations to deliver accurate simulations [25,26]. This paper proposes a simplified fracture strain envelope by replacing the pressure sensitivity function in the modified Xue model by a stress triaxiality function derived from the void growth model originally proposed by Rice [27]. This simplification allows calibration of the fracture strain envelope solely from a single set of uniaxial tension tests. The validation of the proposed fracture model includes both tension tests reported in the existing literature and large-scale tubular joint tests performed in Tongji University. It should be noted that in the simulation of the experiment of CHS–RHS X-joint which experienced the punching shear fracture, the newly proposed fracture model has huge advantages against others (VGM model, etc.), for the Lode angle effect is included to simulate the "shear fracture mode" and the work of parameter calibrations becomes significantly simplified.

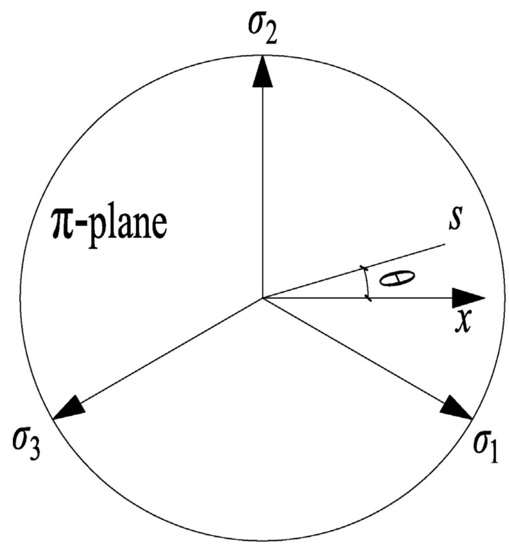

Fig. 1. Lode angle of principal stresses.

2. Fracture model

2.1. Background

The Xue model predicates on the continuum theory of damage plasticity. The damage, measured by a parameter D, depends on the plastic deformation, and accumulates with the increasing equivalent plastic strain. As the damage evolves, the material undergoes strain-softening and degradation in the elastic modulus. When the damage variable D reaches a certain value ($D = 1$), the material fails by fracture and loses all of its strength.

In the Xue model, the damage accumulation rule follows Eqs. (1)–(2),

$$D = \int_0^{\varepsilon_p} \dot{D} d\varepsilon_p \tag{1}$$

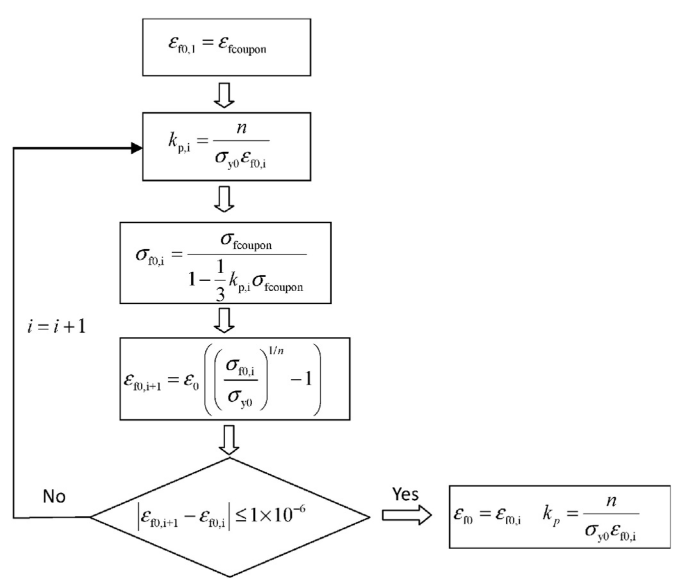

Fig. 2. Simplified procedure for parameter calibrations in the modified Xue model.