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Material characterization using finite element deletion strategies for collapse modeling of steel structures

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ABSTRACT

The prediction of collapse of structures has gained growing attention recently, as it is important to be able to predict and model structural collapse due to extreme loads. A lack of accurate, pragmatic, and validated structural collapse models currently limits the capabilities for predicting collapse due to possible extreme loads. This research compares three finite element deletion strategies that account implicitly for fracture under monotonic loading to be used as predictive tools for collapse modeling of steel structures. The first strategy employs a Void Growth Model (VGM) to simulate the initiation of softening and the Hillerborg model for modeling of material softening, followed by an element deletion strategy that is developed in this framework. The second strategy adds a Bao-Wierzbicki model to the VGM strategy (VGM-BW) in order to account more directly for fracture initiation in lower and negative triaxiality regions. The third strategy is a constant critical strain (CS) approach that does not include softening but instead deletes an element when it achieves a peak equivalent plastic strain. The parameters of the VGM strategy were calibrated to a comprehensive set of experimental test results of circumferentially notched tensile (CNT) coupon specimens, the Bao-Wierzbicki parameters in VGM-BW strategy were determined analytically through tensile coupon (TC) specimens, and the CS approach used a constant value for equivalent plastic strain at softening initiation. These strategies were then validated through comparison with experimental test results of specimens commonly used for material characterization of steel. The results establish the accuracy and effectiveness of the VGM strategy for high-fidelity parametric simulation capabilities for collapse of steel structures and provide recommendations for where additional experimental research is needed to validate regions of low and negative triaxiality.

1. Introduction

To study the behavior of steel structures under collapse, a model needs to account accurately for fracture and complete material separation in steel members. It has been reported that ductile fracture governs fracture initiation in steel structures during collapse [1–3]. To account for material separation and fracture in steel members, a common approach taken in recent years is to use finite element deletion strategy. The collapse of steel structures was often studied through finite element models that employed a constant critical strain (CS) strategy to account for deletion of finite elements to simulate fracture [4,5]. In this approach, one provides a critical value for equivalent plastic strain at which to delete an element without any softening being implemented [6]. A common value of this strain has been 0.2 in collapse modeling of steel structures, while some researchers calibrated this value to target certain stress-strain conditions [7,8]. For CS to give accurate results, this approach typically requires recalibration of the equivalent plastic strain at fracture initiation for different states of stress and strain because it is independent of stress triaxiality, defined by Eq. (1), where σ_m is mean stress and $\bar{\sigma}$ is von Mises stress [6,8]:

$$T = \frac{\sigma_m}{\bar{\sigma}} \tag{1}$$

Most of the time, this is difficult because accurate calibration of this failure strain parameter for particular loading and boundary

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conditions in steel structures is best compared to full-scale experimental test results. To avoid the need for recalibration, and to be able to use small-scale coupons instead of full-scale experimental test results for calibration of finite element deletion strategies, an approach should be used that is based on ductile fracture assumptions and accounts for stress triaxiality variation in the finite element to be deleted [9–12]. In this research, a comparison is made between the constant strain approach that is common in the literature and two strategies, Void Growth Model (VGM) and VGM plus Bao-Wierzbicki (VGM-BW), that use ductile micromechanical fracture initiation models to account for fracture initiation and a Hillerborg model to account for softening of the material leading to element deletion, which simulates material separation [9,13,14]. The Bao-Wierzbicki model attempts to account for fracture at lower triaxiality [15]. The three strategies are calibrated and then validated through comparison to small-scale structural steel specimens. In a companion paper [16], the results are validated to a wide range of full-scale experiments of structural steel connections and frames.

2. Collapse modeling using element deletion approach

To properly model collapse of steel structures using finite element analysis, one needs to account for material separation. In this research, three finite element deletion strategies, VGM, VGM-BW, and CS, are compared to each other in modeling fracture and material separation. Softening is implemented after fracture initiation through the Hillerborg damage model, and a finite element is eliminated from the mesh if the effective stress reaches a value of zero at the Gauss point in the element. In the CS strategy, the softening is ignored after fracture initiation and the element is deleted immediately at peak effective stress when the value of equivalent plastic strain is reached at any Gauss point in the element [17]. The material nonlinear formulation is developed in conjunction with using a von Mises yield surface with associated plastic flow and isotropic hardening behavior. These formulations for fracture initiation and softening are available for the central difference algorithm used for time history analysis in the ABAQUS/Explicit finite element software [18] utilized in this work. An updated Lagrangian geometrical nonlinear element formulation that includes large strains is also used [18]. Elements are formulated in the current configuration using current nodal positions. Contact is modeled using a balanced master-slave contact pair formulation that uses sophisticated algorithms for tracking the motions of the surfaces to resist node into face and edge into edge penetration [18]. Contact constraints are enforced through a kinematic constraint enforcement and penalty methods [18].

VGM is a phenomenological model of fracture initiation due to void nucleation, growth, and coalescence inside ductile material [13]. A fundamental assumption of the model is that the critical equivalent plastic strain is a function of stress triaxiality expressed by Eq. (2). The Bao-Wierzbicki model assumes a different relationship of equivalent plastic strain to triaxiality where it captures lower triaxiality regions. The complete criteria for fracture initiation in VGM-BW strategy is provided in Eq. (3). The fracture initiation criterion in CS strategy is expressed by Eq. (4), assuming a constant strain value of 0.2 that is common in the literature [4,5]. The criteria for fracture initiation is met when the integral of the ratio of equivalent plastic strain at an integration point of an element to critical equivalent plastic strain as a function of triaxiality equals 1, expressed by Eq. (5) [19].

$$\bar{\varepsilon}_{FI}^{pl}(T) = \begin{cases} \infty & T \leqslant 0 \\ \eta e^{-\beta T} & 0 \leqslant T \end{cases} \tag{2}$$

$$\bar{\varepsilon}_{FI}^{pl}(T) = \begin{cases} \infty & T \leqslant -1/3 \\ C_1/(1+3T) & -1/3 < T \leqslant 0 \\ C_1 + (C_2 - C_1)(T/T_o)^2 & 0 < T \leqslant T_o \\ \eta e^{-\beta T} & T_o \leqslant T \end{cases} \tag{3}$$

$$\bar{\varepsilon}_{FI}^{pl} = 0.2 \quad -\infty \leqslant T \leqslant \infty \tag{4}$$

$$\int^{d} \bar{\varepsilon}^{pl}/\bar{\varepsilon}_{FI}^{pl}(T) = 1 \tag{5}$$

where:

- T – triaxiality
- σ_m – mean stress
- $\bar{\sigma}$ – von Mises equivalent stress
- $\bar{\varepsilon}_{FI}^{pl}(T)$ – critical equivalent plastic strain at fracture initiation
- β – material property constant
- η – material capacity constant
- C_1 – $\bar{\varepsilon}^{pl}$ at 0 triaxiality
- C_2 – $\bar{\varepsilon}^{pl}$ at 1/3 triaxiality
- T_0 – triaxiality in uniaxial state of stress = 1/3

For calibration and validation, triaxiality, equivalent plastic strain, and other stress-strain related properties are calculated at the integration point of each finite element. The value of this integral in Eq. (5) would increase at each time increment of the analysis monotonically with an increase in plastic deformation. During the unloading, the value of the integral does not change and the unloading occurs at a slope equal to the current Elastic Modulus. Upon reaching a value of 1.0, the fracture initiation criterion is met and material softening subsequently takes place for the VGM and VGM-BW strategies [18]. For CS strategy, when the integral equals 1, the element is deleted.

Softening of the element in VGM and VGM-BW is modeled through a Hillerborg Model [14]. The damage manifests itself through isotropic softening of the yield surface and degradation of modulus modeled by Eqs. (6) and (7), respectively. During softening, spatial mesh dependency is introduced based on strain localization, which causes dissipated energy to decrease as the mesh is refined [18]. A stress-displacement relationship has thus been proposed in the literature to mitigate localization [14]. This is achieved through defining a material parameter that describes the energy required to open a unit area of crack, G_f. The fracture energy is then given by Eq. (8).

$$\bar{\sigma}_S = (1 - D)^* \bar{\sigma}_{NS} \tag{6}$$

$$E_s = (1 - D)^* E \tag{7}$$

$$G_f = \int_{\bar{\varepsilon}_{FI}^{pl}}^{\bar{\varepsilon}_f^{pl}} L\sigma_y d\bar{\varepsilon}^{pl} = \int_0^{\bar{u}_f^{pl}} \sigma_y d\bar{u}^{pl} \tag{8}$$

where:

- $\bar{\sigma}_S$ – equivalent stress with softening accounted for
- $\bar{\sigma}_{NS}$ – equivalent stress without any softening being modeled
- D – damage variable
- E_s– modulus modified to account for softening
- E – elastic modulus
- G_f– fracture energy
- $\bar{\varepsilon}_{FI}^{pl}$ – equivalent plastic strain at fracture initiation
- $\bar{\varepsilon}_f^{pl}$, $\bar{u}_f^{pl}$ – equivalent plastic strain, displacement at element deletion, respectively
- L – characteristic length
- σ_y – yield stress