Eleventh U.S. National Conference on Earthquake Engineering
Integrating Science, Engineering & Policy
June 25-29, 2018
Los Angeles, California

SIMULATION OF DUCTILE FRACTURE PROPAGATION IN STRUCTURAL STEEL SUBJECTED TO ULTRA-LOW CYCLE FATIGUE

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ABSTRACT

While considerable progress has been made in simulating the overall seismic response of steel structures using nonlinear response history (dynamic) analysis, techniques to simulate fracture propagation under large scale inelastic cyclic loading are not as well developed. This is despite the fact that fracture is often a critical limit state that can precipitate structural failure and collapse. To address this, a new ductile damage-based cohesive zone model is presented. The proposed model is an extension of the established continuum-based local or micromechanical ductile fracture models for evaluating ultra-low cycle fatigue in structural steels. This model is implemented in the finite element program WARP3D, and evaluated against tests of notched bars that fail by ductile crack propagation. The preliminary results indicate that the model is an effective tool for predicting ductile fracture initiation and propagation in structural steels subjected to monotonic and cyclic large scale inelastic loading. Implications of this for characterizing the post-fracture response of structural steel components are discussed, along with limitations of the research.

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Simulation of ductile fracture propagation in structural steel subjected to ultra-low cycle fatigue

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ABSTRACT

While considerable progress has been made in simulating the overall seismic response of steel structures using nonlinear response history (dynamic) analysis, techniques to simulate fracture propagation under large scale inelastic cyclic loading are not as well developed. This is despite the fact that fracture is often a critical limit state that can precipitate structural failure and collapse. To address this, a new ductile damage-based cohesive zone model is presented. The proposed model is an extension of the established continuum-based local or micromechanical ductile fracture models for evaluating ultra-low cycle fatigue in structural steels. This model is implemented in the finite element program WARP3D, and evaluated against tests of notched bars that fail by ductile crack propagation. The preliminary results indicate that the model is an effective tool for predicting ductile fracture initiation and propagation in structural steels subjected to monotonic and cyclic large scale inelastic loading. Implications of this for characterizing the post-fracture response of structural steel components are discussed, along with limitations of the research.

Introduction

Approaches to predict earthquake-induced fracture due to inelastic cyclic loading have made considerable progress since the widespread fractures that occurred in the 1994 Northridge and 1995 Kobe earthquakes. Significant among these are micromechanics-based or "local" fracture models, which are capable of predicting fracture initiation during Ultra-Low Cycle Fatigue (ULCF) earthquake loading [1]. Unlike classical fracture mechanics models, which operate on the far-field stress state and are not well suited to situations with large-scale yielding, these "local" models are widely applicable to structural engineering situations, such as post-Northridge steel connections as outlined in FEMA 350 [2], and in corners of structural elements or in shear bands which have low stress triaxiality. As a result, they are increasingly used by the research and engineering communities [1,3,4].

Whereas most previous research has focused on ductile crack initiation, there is a lack of validated models and technologies to simulate ductile crack propagation under large-scale cyclic

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loading of steel structures. This implies that crack initiation itself must be conservatively presumed an indicator of structural failure. However, work by Myers et al. (2009) indicates that ULCF initiated cracks may show significant stable propagation before brittle fracture occurs, thus demonstrating a significant limitation in the current framework for likelihood calculations of extreme fracture limit-states [5]. As the design paradigm of critical structures in seismic areas shifts towards reliability-based performance assessment, this limitation becomes increasingly prominent. Motivated by this background, this research introduces and demonstrates a new computational model to simulate ductile fracture propagation.

Framework for Simulation of Ductile Fracture Propagation

This work builds upon the stress-weighted damage model (SWDM) by Smith et al. (2014), which has been extensively validated for ULCF and low stress triaxiality situations [6]. The functional form of the SWDM is provided in Eq. 1:

$$D_{SWDM} = C\exp\left(\lambda\varepsilon_{acc}\right)\int\limits_{loading}\left[\exp\left(1.3T\right)-\exp\left(-1.3T\right)\right]\exp\left(\kappa\left|\xi\right|\right)d\varepsilon_{p} \qquad (1)$$

where ε_{acc} is the accumulated plastic strain, T is the stress triaxiality, ξ is the normalized Lode angle parameter, and C, λ, and κ are calibrated material parameters. The SWDM is a micromechanics-based model for microvoid growth and coalescence associated with ductile fracture. This is an uncoupled fracture criterion, which predicts ductile fracture initiation as a post-processing check without simulating crack extension.

Existing numerical schemes for simulating crack extension in finite elements can be broadly placed into three categories: (1) node release or XFEM, (2) cohesive zone models, or (3) element softening and extinction. The proposed framework adopts a cohesive zone numerical scheme, which is advantageous because (1) the stress/strain fields ahead of the crack front are regularized, unlike with node release or XFEM where these fields are singular, (2) a spurious mesh dependency is not introduced, unlike with constitutive softening models, such as the popular Gurson approach, and (3) traditional material models may be used for the continuum elements that neighbor the cohesive zone, avoiding the need to recalibrate established material parameters. Traditional cohesive zone models employ uniaxial descriptions of the fracture stress (so-called traction-separation relationships), which also serve as closing tractions [7]. These closing tractions regularize the stress/strain fields ahead of the crack front, avoiding the unphysical singularity that arises due to continuum elasticity theory [8]. However, this type of fracture description is challenging to implement for ULCF, given its stress-strain history dependency.

A non-local formulation is adopted to address this challenge, so that the traction-separation relationship of a cohesive element may be defined as a function of the SWDM damage in the adjacent solid elements. Using this scheme, fracture propagation is simulated via SWDM damage itself, rather than uniaxial stress (as in the traditional cohesive zone formulation). This new formulation, a ductile-damage based cohesive zone model, is implemented in the finite element code WARP3D, an open source research platform designed specifically to simulate nonlinear fracture [9]. The model provides additional flexibility compared with traditional cohesive zone models, allowing for accurate simulation of ductile fracture propagation.

Results

To demonstrate the efficacy of this framework, simulations are compared with experimental test results of high-performance bridge steel, HPS70W, from Kanvinde and Deierlein (2004) [10]. Figure 1 shows the experimental test result and corresponding FE simulation of a load-deformation curve of a circumferentially notched test (CNT) specimen, where the sudden change in slope at about 0.07 inches displacement indicates ductile fracture initiation and ductile tearing. An FE simulation utilizing the proposed model is able to capture the entire load-deformation response, including both the point of fracture initiation as well as the stiffness degradation due to ductile tearing, up to the point of brittle cleavage. Although this is a simple demonstration, it illustrates the capability of the proposed model to simulate ductile crack propagation under cyclic and low stress triaxiality loading scenarios.

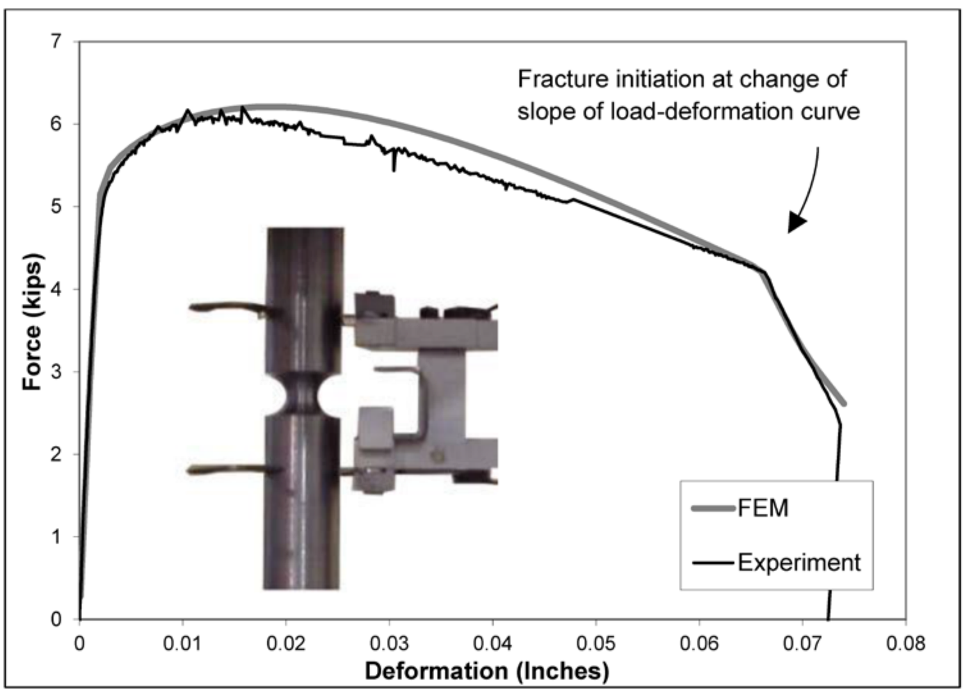

Figure 1. Load-deformation curve of a circumferentially notched specimen.

This is an ongoing research project. Further testing of notched bars, plates, and other specimens are underway to calibrate and validate the proposed model. Modification of the framework to consider brittle cleavage is planned. Afterward, the model will be applied to simulate fracture propagation in buckling-restrained braces, column-baseplate connections, and other steel components of buildings.

Conclusions

A new model for predicting ductile crack propagation is proposed, which is capable of simulating the strength and stiffness degradation of structural components after fracture initiation. This model allows analysts to simulate fracture propagation in concert with global analysis, so that interactions between the structural behavior and propagating crack front may be determined. As such, this model enables accurate reliability quantification during post-fracture response.

Acknowledgments

This paper is based upon collaborative research supported by the National Science Foundation (CMMI Award #1634291 and #1635043). Advice provided by Dr. Robert Dodds Jr. (University of Illinois) is gratefully acknowledged.

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