DEVELOPMENT AND VALIDATION OF A COMPUTATIONAL FRAMEWORK TO SIMULATE DUCTILE CRACK PROPAGATION IN STEEL STRUCTURES DUE TO ULTRA-LOW CYCLE FATIGUE USING WARP3D

Andy Ziccarelli[1]*, Amit Kanvinde[2], and Gregory Deierlein[3]

[1]*North Carolina State University, Raleigh, NC, USA,* [2]*University of California, Davis, CA, USA*
[3]*Stanford University, Stanford, CA, USA*
** Presenting Author email: ajziccar@ncsu.edu*

Abstract
Ductile cracks which form in steel components of civil structures due to ultra-low cycle fatigue may display significant growth prior to component failure. A computational framework was developed to simulate the growth of ductile cracks in structural steel utilizing the WARP3D platform. The basic model formulation is presented, followed by selected results from a small-scale experimental testing program. Results of simulations utilizing the proposed framework demonstrate good agreement with the experimental results.

1. Introduction

Over the past several decades, micromechanics-based continuum rupture criteria have been developed which can predict the initiation of ductile cracks in steel structures under to complex loading conditions, including ultra-low cycle fatigue. The use of continuum-based rupture criteria is essential because modern steel structures are designed and detailed to mitigate sharp cracks, and may experience widespread yielding and cyclic loading. These conditions violate the restrictions of conventional fracture mechanics (K_I, J_I, CTOD) indices.

In large-scale experimental tests of structural steel components under cyclic loading, it has been observed that after a ductile crack initiates due to ultra-low cycle fatigue, considerable propagation of the ductile crack (up to 15 mm) may occur prior to component failure. Therefore, in order to accurately characterize component behavior under extreme loads, there is a need to develop computational methods which can simulate this ductile crack propagation.

2. Framework

The proposed computational framework utilizes cohesive interface elements to simulate crack propagation within a continuum finite element setting. Conventional application of cohesive elements requires prescribing the governing traction-separation relationship (TSR) *a priori*, where the peak cohesive traction effectively serves as the rupture criterion. However, in steel structures subjected to ultra-low cycle fatigue, fracture initiates due to a combination of stress state, plastic strain and loading history, which is reflected in continuum rupture criteria. Therefore, in this framework the continuum rupture criterion is integrated into the cohesive zone model, and is used to inform the governing traction-separation relationship.

An overview of the framework is shown in Fig 1. Cohesive elements are inserted along the anticipated crack plane. In each of the surrounding continuum elements, the continuum rupture criterion is calculated. Once the rupture criterion is satisfied in the neighboring continuum elements, the cohesive TSR is established, based on the current value of traction carried in the cohesive element. Constitutive rules governing the post-initiation response are specified which allow for modeling of crack propagation under both monotonic and cyclic loading conditions.

The following features of WARP3D were leveraged to implement this framework for simulating ductile crack propagation:

- Nonlocal capabilities: Material state variables from continuum elements were accessible to adjacent cohesive elements, which allowed for adaptive updating of the cohesive TSR based on the nearby continuum.

- UMAT interface: Taking advantage of recent developments in modeling the constitutive response of steel under cyclic loading, user materials were obtained from the structural steel research community in the form of UMAT files, which were integrated into analyses using WARP3D.
- Domain integral calculation: The procedures to calculate J provided in WARP3D were utilized to develop simulated J-R curves for sharp-cracked compact tension specimens, which were then compared to experimental data.

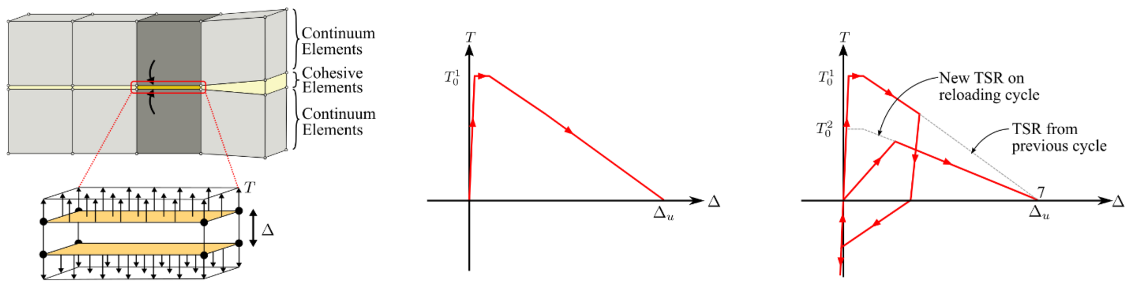

Figure 1. Overview of computational framework (a) schematic of interface cohesive elements, (b) cohesive TSR under monotonic loading and (c) cohesive TSR under cyclic loading

3. Results Summary

An experimental program consisting of 44 specimens was completed to provide data for calibration of the model parameters and for model validation. Specimens tested include Cylindrical Notched Tension bars, Sharp-Cracked Compact Tension specimens and Blunt Notch Compact Tension specimens. The experimental program was designed to span a range of stress states and crack front conditions, and specimens were tested under both monotonic tension and reversed cyclic loading conditions. Results from selected experiments are presented in Fig. 2. In Fig. 2(a), experimental J-R curves are compared to the simulated J-R curve obtained using the proposed framework. In Fig. 2(b), the overall force-deformation response of a Blunt Notch Compact Tension specimen subjected to cyclic loading is presented. In both cases, a good match may be observed between the simulation and the experiments.

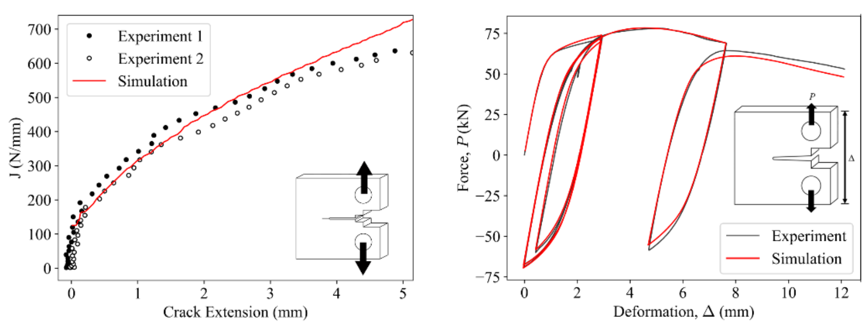

Figure 2. Comparison of experimental and simulated results (a) Sharp-Cracked Compact Tension Specimen and (b) Blunt Notch Compact Tension Specimen

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