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A Computational Framework to Predict Ductile Tearing Effects in Structural Materials

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ABSTRACT

This study describes a 3-D computational framework to model stable extension of a macroscopic crack under mode I conditions in ductile metals. The Gurson-Tvergaard dilatant plasticity model for voided materials describes the degradation of material stress capacity. Fixed-size, computational cell elements defined over a thin layer at the crack plane provide an explicit length scale for the continuum damage process. Outside of this layer, the material remains undamaged by void growth, consistent with metallurgical observations. An element vanish procedure removes highly voided cells from further consideration in the analysis, thereby creating new traction-free surfaces which extend the macroscopic crack. The key micro-mechanics parameters are D, the thickness of the computational cell layer, and f_0, the initial cell porosity. Computational and experimental studies are described for a modified boundary layer (MBL) model with $T=0$ and a conventional C(T) specimen without sidegrooves. The computational models prove capable of predicting the measured R-curves, post-test measured crack profiles, and ductile tearing effects on crack-tip stress fields.

KEYWORDS

Ductile tearing, computational cells, structural integrity, finite elements, R-curves

INTRODUCTION

The stable tearing of a macroscopic crack in ductile materials for structural applications, such as steel alloys and aluminum, is conventionally characterized by crack growth resistance (J–Δa) curves using the J-integral to describe the intensity of near-tip deformation. Since additional load-carrying capacity in structural components is gained if some amount of stable crack growth is allowed, a large number of engineering applications, particularly predictions of mechanical behavior and defect assesements of in-service structures, currently centers on methodologies based upon measured R-curves. Specifically, large increases of J above the onset of ductile crack extension (J_{Ic}) are possible in materials with high tearing resistance with considerable practical consequences to design and structural flaw analysis. Moreover, ductile tearing often preceeds cleavage fracture in structural steels operating in the ductile-to-brittle (DBT) region as small amounts of stable crack growth alter significantly the stress fields which govern the propensity to trigger cleavage. Consequently, realistic methodologies for fracture assessments of structural components must include advanced procedures capable of modeling crack extension.

This study extends the *computational cell* framework, originally developed in a 2-D context by Xia and Shih (X&S) (1995a, 1995b), into a 3-D setting capable of modeling mode I crack extension. Applications of this 3-D framework readily include, for example, surface breaking defects as well as conventional, through-thickness fracture specimens (with and without sidegrooves). In the computational cell model, ductile crack extension occurs through void growth and coalescence (by cell extinction) within a thin layer of material symmetrically located about the crack plane. An element vanish procedure removes highly voided cells from the analysis thereby creating new traction-free surfaces which extend the macroscopic crack. The cells have initial (smeared) void volume fraction denoted by f_0. The layer thickness (D) introduces a strong length-scale over which damage occurs; elsewhere, the background material obeys the flow theory of plasticity without damage by void growth. The 3-D form of the Gurson-Tvergaard (GT) dilatant plasticity theory [Gurson, 1977, Tvergaard, 1990] provides a suitable description of void growth within the cells. Our exploratory 3-D studies using computational cells clearly demonstrate the capability to predict severe tunneling in non-sidegrooved specimens and to