International Journal of Plasticity 27 (2011) 920–939

Contents lists available at ScienceDirect

International Journal of Plasticity

journal homepage: www.elsevier.com/locate/ijplas

Effects of the strain-hardening exponent on two-parameter characterizations of surface-cracks under large-scale yielding

Shawn A. English, Nagaraj K. Arakere *

Department of Mechanical and Aerospace Engineering, University of Florida, Gainesville, FL 32611-6300, USA

ARTICLE INFO

Article history:
Received 29 June 2010
Received in final revised form 9 September 2010
Available online 30 October 2010

Keywords:
Surface cracks
Constraint effects
Finite element analysis
Large-scale yielding
Ductile fracture

ABSTRACT

The influence of strain hardening exponent on two-parameter *J*–*Q* near tip opening stress field characterization with modified boundary layer formulation and the corresponding validity limits are explored in detail. Finite element simulations of surface cracked plates under uniaxial tension are implemented for loads exceeding net-section yield. The results from this study provide numerical methodology for limit analysis and demonstrate the strong material dependencies of fracture parameterization under large scale yielding. Sufficient strain hardening is shown to be necessary to maintain *J*–*Q* predicted fields when plastic flow progresses through the remaining ligament. Lower strain hardening amplifies constraint loss due to stress redistribution in the plastic zone and increases the ratio of tip deformation to *J*. The onset of plastic collapse is marked by shape change and/or rapid relaxation of tip fields compared to those predicted by MBL solutions and thus defining the limits of *J*–*Q* dominance. A radially independent *Q*-parameter cannot be evaluated for the low strain hardening material at larger deformations within a range where both cleavage and ductile fracture mechanisms are present. The geometric deformation limit of near tip stress field characterization is shown to be directly proportional to the level of stress the material is capable of carrying within the plastic zone. Accounting for the strain hardening of a material provides a more adjusted and less conservative limit methodology compared to those generalized by the yield strength alone. Results from this study are of relevance to establishing testing standards for surface cracked tensile geometries.

1. Introduction

Plastic deformation precedes fracture in metals and their alloys and resistance to fracture is therefore directly related to the development of the plastic zone at the crack tip. Among the major causes of metallic structural failure is the nucleation and propagation of cracks from regions of high stress concentration such as notches and surface flaws, due to both monotonic and fatigue loading. Understanding the evolution of plasticity in notches and cracks is therefore important for predicting fracture behavior of critical load bearing structures in many engineering applications. Consequently, development of crack tip elastic–plastic fields, as a function of load configuration, geometry, monotonic and cyclic strain hardening behavior, and constraint effects have been subject of intensive study.

Behavior of the crack tip in the plastic zone for strain hardening materials under small-scale yielding for symmetric (Mode I) or antisymmetric (Mode II) two-dimensional (2D) stress distribution has been presented in the widely referenced HRR articles by Hutchinson (1968a, b) and Rice and Rosengren (1968). Extensions to combinations of Mode I and Mode II loadings were presented by Shih (1973, 1974). Comprehensive literature reviews of plane-strain fracture mechanics and

* Corresponding author. Tel.: +1 352 392 0856; fax: +1 352 392 1071.
E-mail address: nagaraj@ufl.edu (N.K. Arakere).

0749-6419/$ - see front matter
doi:10.1016/j.ijplas.2010.10.002

Nomenclature

t	thickness
L	half length
l	general characteristic length
w	half width
a	crack depth
c	half crack width
r	radial distance from crack tip
J	J-integral
T	T-stress
Q	near crack stress difference parameter
σ_o	reference yield stress
ε_o	yield strain
n	strain hardening exponent for a linear plus power law material
σ_∞	far-field stress in the loading direction
σ_{Net}	average stress in the opening direction over the remaining area in the crack plane
δ	far-field displacement
u_y	crack tip blunting displacement
θ	angle in plane perpendicular to crack front, $\theta = 0°$ is in the growth direction
ϕ	angle measured along the crack front in the crack plane

crack tip field characterization are found in Anderson (2004), Irwin and Paris (1971), McClintock (1971), Panayotounakos and Markakis (1991), Rice and Rosengren (1968).

The aforementioned papers refer to fracture prediction using single parameter (K for brittle fracture and J for ductile fracture) crack tip field characterizations. The J-integral alone does not uniquely and accurately describe the crack tip fields and resistance against initiation of ductile crack growth when constraint effects arising from geometry and load configuration are considered. The constraint can be thought of as a structural obstacle against plastic deformation induced mainly by the geometrical and physical boundary conditions (Yuan and Brocks, 1991). Constraint effects can also arise from mismatch of material properties in a heterogeneous joint (English et al., 2010). Under these conditions, a second parameter, in addition to the J or K, is introduced to quantify the crack tip constraint. Crack tip triaxiality, which is defined as the ratio of hydrostatic pressure to von Mises stress, or a parameter that maintains a linear relationship with triaxiality, can be used as a constraint parameter for predicting ductile crack growth. The in-plane constraint is influenced by the specimen dimension in the direction of crack growth or the length of the uncracked ligament, and by global load configuration (bending or tension), whereas the out-of-plane constraint is controlled by the specimen dimension parallel to the crack front or the specimen thickness, for thorough-thickness cracks (Giner et al., 2010). Out-of-plane constraint is typically denoted as a plane-strain (high triaxiality) or plane-stress (low triaxiality) state. In finite thickness fracture geometries, where the points are embedded entirely in material, there exists a state of plane-strain near the crack tip, the exception being very thin films (O'Dowd, 1995; Shih and O'Dowd, 1993; Wang, 2009).

1.1. J-T and J–Q characterization of near tip fields

Williams (1957) showed the existence of a non-singular in-plane normal stress component (T-stress) for linear elastic material. The significance of the T-stress on the size and shape of the plastic zone under small-scale yielding (SSY) conditions was shown by Larsson and Carlsson (1973), Rice (1974), O'Dowd and Shih (1991, 1992), Sharma and Aravas (1991) show the important role played by higher order terms in asymptotic solutions of crack tip fields and demonstrate that a two-parameter characterization of the crack tip fields involving J and a triaxiality or constraint parameter Q is necessary to satisfactorily describe the configuration dependence of fracture response of isotropic plastic solids, particularly under large scale yielding conditions. The use of a single parameter characterization (K or J) is limited to geometries that maintain a high constraint, such as the compact tension (C(T)) specimen, where the in-plane stresses are dominated by bending. The Q stress difference factor has been found to maintain a material dependent linear relationship with near tip triaxiality independent of geometry, dimensions and deformation level. Moreover, the Q factor is shown to accurately predict near tip stress and strain fields, particularly plastic strains, and therefore can be used as a ductile fracture parameter (Henry and Luxmoore, 1997; Kikuchi, 1995).

A significant body of work has focused on two-parameter characterization of through-thickness cracks while limited work has been done on surface crack geometries. Wang (1993) established the two-parameter characterization with modified boundary layer (MBL) reference solutions to topographical planes perpendicular to the crack front in surface crack tension (SC(T)) and surface crack bend (SC(B)) geometries. Wang (2009) investigated Q as a function of load and radial distance from the crack tip for surface crack uniaxial and biaxial tension models.