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The effects of nonproportional loading on the elastic-plastic crack-tip fields

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ABSTRACT

In this paper, the biaxial loading path effects on the mode I plane strain elastic-plastic crack-tip stress fields are investigated computationally. First, three different loading sequences including one proportional loading and two non-proportional loading paths are applied to the modified boundary layer (MBL) model under small-scale yielding conditions. For the same external displacement field applied at the outer boundary of the MBL model, the mode I K field and T-stress field combined as the different loading paths are applied to investigate the influence of the nonproportional loading. The results show that for either the compressive or tensile T-stress, the loading path which applied K field first followed by T-stress field generates the lower crack-tip constraint comparing to proportional loading. There is only minor difference between the results from proportional loading path and that with the T-stress field applied first following by K field. Next, two finite width specimens under non-proportional biaxial loading conditions that generate the same three loading paths are analyzed. Similar crack tip characteristics are observed in these specimens as these obtained from the MBL model, and it is demonstrated that the near-tip behavior in specimens can be predicted accurately using the results from MBL models. The present results show that it is very important to include the load sequence effects in elastic-plastic fracture analysis when dealing with nonproportional loading conditions.

1. Introduction

In the past twenty-five years, significant progress has been made in understanding the effects of crack-tip constraint. It is now well-established that crack tip stress fields can be characterized using two parameters, i.e. the crack driving force, J and a constraint parameter. The most widely used constraint parameters are T-stress, Q-factor and A_2-term, corresponding to J-T, J-Q, or J-A_2 framework [1–4]. On the other hand, the experimental testing methods for measuring fracture toughness under varying constraint conditions have also been developed accordingly (see Ref. [5]).

However, majority of the above development has been focused on the cases where the external loading is applied proportionally. In engineering structural components, there are many situations where the external loads are bi-axial or multi-axial, and are applied non-proportionally. For example, the mechanical and thermal operating loads or residual stresses can introduce a complex combination of primary and secondary biaxial loads in a structural integrity assessment for pressure vessels. The effects of biaxial proportional loading on constraint have been an active research topic recently, see

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Nomenclature

a	crack depth
A_2	constraint parameter (second fracture parameter) in J-A or J-A_2 crack-tip fields
B	biaxial load ratio
b	diameter of local notch at crack tip
CCP	centre cracked plate
E	elastic modulus (Young's modulus)
h	normalized hydrostatic stress
J	J-integral
K_I	mode I stress intensity factor
MBL	modified boundary layer
n	material hardening exponent
Q	constraint parameter in J-Q crack tip fields
r	radius in polar coordinates at crack tip
r, θ	cylindrical coordinates
r_0	radius of local notch at crack tip
r_{max}	maximum radius of the modified boundary layer model
r_p	plastic zone size
SECP	single edge cracked plate
SSY	small-scale yielding
T	T-stress
u_x, u_y	boundary displacement components in x and y directions of cartesian coordinates
x, y	Cartesian coordinates
υ	Poisson's ratio
α	material coefficient in Ramberg-Osgood relationship
ε_{ij}	strain components
σ_{ij}	stress components
ε_y	yield strain
σ_y	yield stress

[6], for example. Thus far, however, few researchers have investigated the biaxial nonproportional loading effects on the crack-tip characteristics. In an early work, Faleskog and Nordlund [7] studied the effects of uniaxial non-proportionally loaded tension and bending loads on the near tip fields. Their investigation showed that the near crack-tip field could be characterized by J-Q theory in the range of small-scale yielding up to fully yielded situations. On the other hand, Lei [8] introduced a modified J-integral for cases involving non-proportional stressing. Ren et al. [9] studied the effect of residual stresses on the crack-tip constraint in a modified boundary layer (MBL) model. It was found that the nonproportional loading path could generate different crack-tip constraint than the proportional loading paths [9].

In addition, it has been shown in several engineering applications, nonproportional loading sequence can has significant effect on the fracture toughness of materials. For example, warm prestressing (WPS) effects have been shown that the fracture toughness of steels in the lower shelf region increases by preloading them at upper shelf region [10]. Further study is required to systematically quantify the effects of non-proportional loading on near-tip crack fields.

The boundary layer (MBL) model, as shown in Fig. 1(a) represents a crack tip model which is widely used for the study of 2D elastic-plastic crack tip fields [1–4]. The model is subjected to K and T-stress fields. Furthermore, in [11–13], the 3D MBL model was used to study the constraint effect by varying T-stress using J-Q and J-A_2 two parameter characterizations for various 3D crack geometry and loading conditions. In all these works, however, the K and T are applied proportionally. In the present work, numerical calculations for MBL model under nonproportional loading conditions under the combination of K and T are carried out, as shown in Fig. 2. In addition, we will also consider single-edge-cracked plate (SECP) and centre-cracked plate (CCP) specimens (Fig. 1(b) and (c)) under non-proportional biaxial loading, to study the effects of the same load paths in specimens. Results from MBL models will be used to predict the behavior in the finite width specimens. The analyses are based on the incremental plasticity and large deformation formulation.

The rest of paper is organized as follows. The backgrounds on crack-tip constraint using J-Q theory are reviewed in Section 2. Finite element models and simulation procedure are presented in Section 3. In Sections 4 and 5, the results for MBL model and specimens subjected to different loading paths are presented, respectively. The conclusions are summarized in Section 6.

2. Theoretical background

It has been shown in [2,3] that a two parameter description, using J-integral and a constraint parameter Q, fully characterizes the near tip stress and strain states in a wide range of 2D plane-strain crack geometries. The Q is a hydrostatic