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On fracture initiation angle near bi-material notches – Effects of first non-singular stress term

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ABSTRACT

The effect of first non-singular stress term of elastic stress field near bi-material notches (I-stress) on the fracture initiation angle is investigated. A modified maximum tangential stress (MMTS) criterion is suggested for predicting the fracture initiation angles which takes into account the effect of I-stress as well as the singular terms. It is shown that the I-stress can play an important role in fracture initiation behavior adjacent the interface corners and neglecting this term may introduce significant errors in predicting the fracture initiation angle. Then, to evaluate the proposed criterion, a finite element (FE) simulation is done on a typical test specimen and the presented criterion is applied for predicting the fracture initiation direction. It was observed that the MMTS predictions are very close to the results obtained from the FE analysis (which takes into account all stress terms) showing the reasonable accuracy of the MMTS criterion for bi-material notch problems.

1. Introduction

In order to manufacture the new generation of structures, the use of bi-material joints is rapidly going to be increased. Nowadays, different kinds of bonding such as welding, soldering and adhesively bonded joints are used in many modern structures. For example, ceramic/ceramic, ceramic/metal and ceramic/glass joints are extensively employed in different industrial structures such as aircrafts, automobiles and microstructures. However, because of the geometry and material discontinuity at the edge of these bonds, high stress gradient leads to initiation micro-cracks which may finally result in fracture [1]. Therefore, the accurate study of stress field at these corners is one of the most important steps for investigating their fracture behavior.

According to the concepts of linear elastic fracture mechanics (LEFM), the elastic stresses at the interface corners approach infinity as a result of stress singularity. The linear elastic stress field for a bi-material notch subjected to remote mechanical loading condition can be expressed by Williams's series expansions in terms of singular and non-singular stress terms. The singular and non-singular terms of elastic stress field around the homogeneous and bi-material notches have been studied by many researchers [1–10]. In the case of bi-material notches, a comprehensive study has been done on the first non-singular stress term by Ayatollahi et al. [5]. They indicated that the first non-singular stress term (called the I-stress) may sometimes be an effective term in evaluating the stress field and neglecting this term can introduce significant errors in characterizing the tangential stress very close to the notch tip. The fracture behavior at the interface corners has

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Nomenclature

a	bi-material notch depth
E_m, υ_m, μ_m	Young's modulus, Poisson's ratio and shear modulus of material m
FEM	finite element method
F	far field loading
f_{ijk}^m, g_{ijk}^m	non-dimensional functions related to material m ($i, j = r, \theta$), $k = 1, \ldots, N$
H_k	stress intensity factor corresponding to the eigenvalue λ_k
I-stress	first non-singular stress term of the bi-material notch
L, W, S	geometrical parameters of the specimens
m	material number
N	number of terms of the bi-material stress field
r, θ	polar coordinate components
d_c^m	critical distance in material m
t	specimen thickness
u_i^m	displacement components in the material m ($i = r, \theta$)
α, β	mismatch parameters
γ	bi-material notch opening angle
θ_1, θ_2	angles characterize the bi-material notch geometry
θ_0^m	fracture initiation angle in material m
κ_m	Kolosov constant related to material m
λ_k	bi-material notch eigenvalues
M^e	mixity parameter
σ_{ij}^m	stress components in the material m ($i, j = r, \theta$)
σ_C^m	critical tensile stress in the material m

also been investigated by many researchers but the concentration was only on the singular terms of the stress field [11–16]. For example, Akisanya and Meng [11] studied the initiation of fracture at the interface corners. But they only considered the singular solution of the stress field and did not take into account the possibility of kinking out of the interface.

On the other hand, in some bonded joints with strong interfaces, the crack may kink into one of the materials instead of growing through the interface [1,16,17]. For structures containing these strong bonds, prediction of the kinking angle is one of the most important steps for service-life evaluation of the bonds. The problem of crack kinking out of the interface for interface cracks and notches has been studied by many researchers mainly considering the effects of singular stress terms alone [16–19].

Several fracture criteria for bi-material/homogeneous notches containing brittle materials have been proposed in the past by many researchers. But, despite of variety in the proposed methods, they can be classified into two basic separated concepts: the stress based methods and the energy based methods. The stress based criteria assume that fracture occurs at a critical distance from the bi-material/homogeneous notches tip along the direction of maximum tangential stress when the tangential stress reaches its critical value. The successful application of maximum tangential stress criterion for predicting the onset of brittle fracture in the specimens containing cracks, sharp notches, rounded tip V-notches and U-notches has also been demonstrated in several papers for homogeneous and bi-material media of brittle materials (see Refs. [18–24]). For energy based criteria, some studies have been done based on the strain energy density concept which suppose that crack initiates at the interface corner in the direction where the strain energy density reaches its minimum [25,26].

Based on the maximum tangential stress (MTS) criterion, fracture at the corners occurs when the value of tangential stress at a critical distance d_c, in front of the bi-material notch tip, reaches its maximum possible value in one of the two materials. The MTS criterion and mean stress criterion, which considers the mean value of tangential stress, are used by many researchers to analyze the fracture behavior of bi-material and homogeneous notches [21–24]. A review of literature reveals that the study of fracture initiation for strong interface corners has been rarely investigated by considering the non-singular stress terms. The aim of this paper is to study the fracture initiation angles of bi-material notches using the modified maximum tangential stress (MMTS) criterion which considers the effects of I-stress in addition to the singular stress terms. First, the effect of I-stress on the fracture initiation angles of bi-material notches is studied for two geometries as well as two material combinations. Then, the MMTS criterion is presented for predicting the fracture initiation angles and its application is investigated and validated using numerical simulation of a typical bi-material notched specimen.

2. Elastic stress distribution near a bi-material notch tip

Consider a general geometrical and material combination of a traction-free bi-material notch as shown in Fig. 1. The bi-material notch can be characterized by the angles θ_1 and θ_2 which respectively correspond to materials 1 and 2. The bi-material notch angle γ can be defined by $\gamma = 2\pi - \theta_1 - \theta_2$.