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On fracture of kinked interface cracks – The role of T-stress

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ABSTRACT

This paper presents a modified maximum tangential stress criterion (MMTS) for prediction of the fracture initiation conditions in kinked bi-material cracks. The criterion takes into account the effect of T-stress as well as the stress intensity factors (K_I and K_{II}) to predict the mixed mode fracture toughness of interface cracked specimens. First the fracture criterion is developed and the effect of sign and magnitude of T-stress on mixed mode fracture toughness is studied analytically. Then, the suggested criterion is evaluated using the experimental data reported for some epoxy/Aluminum Brazil-nut-sandwich specimens in the literature. The MMTS criterion is also compared with the conventional maximum tangential stress (MTS) criterion and hence, significantly improved estimates were achieved for mixed mode fracture toughness of the tested specimens.

1. Introduction

Bi-material joints can be seen as a part of many industrial and engineering structures. For example, bonding components made of concrete/rock, silicon/glass, ceramic/metal and composite/metal are extensively used in civil engineering structures, electronic devices, automobiles and aircrafts [1–6]. At the interface of bi-material components, cracks may create as a result of imperfect bonding or during the service life of the structures containing these bonds. Since the bi-material cracks are often under mixed mode loading conditions, because of the asymmetry in material property at the interface, they usually kink into one of the materials in strong interfaces [2,5,6].

Several fracture criteria are proposed in the past by many researchers for prediction of the fracture initiation conditions of bi-material/simple cracks and notches. Although one can find a number of proposed fracture criteria in the literature, they can generally be classified into the two basic categories: energy based and stress based criteria.

For the energy based criteria [7–12], Berto and lazzarin [11,12] presented a comprehensive review of some local approaches applicable near stress raisers both sharp and blunt. He and Hutchinson [8] proposed a fracture criterion for kinked bi-material cracks based on the energy release rate, G, concept. They indicated that fracture at the bi-material crack tip occurs in direction where the energy release rate is maximum and kinking conditions depends on relative toughness of the interface. Despite using a realistic fracture mechanics concept, the G criterion did not able to show the role of each fracture mode (opening, mode I and sliding, mode II) and higher order terms of stress field.

Among the stress based criteria, Yuuki and Xu [13] have proposed a fracture criterion for kinked interface cracks using the maximum tangential stress (MTS) concept. They have indicated that the MTS criterion, which had been used previously for simple cracks [14], is capable of successfully predicting the direction and onset of fracture initiation at the bi-material crack tip. Based on this criterion, an interface crack propagates in direction where the tangential stress, $\sigma_{\theta\theta}$, reaches to its critical value, σ_c, in one of the materials. The advantage of using MTS criterion than energy based ones was simplicity and distinction of the role of each fracture mode (K_I and K_{II}). Although their work was a good attempt toward proposing a simple fracture criterion, it was limited to special combination of materials at the interface. They also only used the singular solution of elastic stress field and did not take into account the effect of higher order terms.

In agreement with the pioneering work done by Irwin [15], recent studies on bi-material/simple cracks and notches indicate the significant effects of first nonsingular term of elastic stress field on fracture behaviour as well as the stress distribution near the crack/notch tip [16–25]. Smith et al. [16] studied the effect of T-stress on fracture behaviour of homogeneous cracks using the MTS criterion. They indicated that the T-stress can play an important role in estimation of fracture initiation angle and mixed mode fracture toughness of homogenous cracks. Mirsayar et al. [22], recently indicated that the first nonsingular stress term of elastic stress field near bi-material notch tip, I-stress, significantly affects on the prediction of fracture initiation angle using MTS criterion. In

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Nomenclature

a	crack length for edge cracks and semi-crack length for center cracks	R, h	geometrical parameters of the Brazil-nut-sandwich specimen
r, θ	polar coordinate components	N	number of terms of the bi-material stress field
K_I and K_{II}	mode I and mode II stress intensity factors	$\theta_0^{(m)}$	fracture initiation angle in material m
T	T-stress	κ_m	Kolosov constant related to material m
m	material number	M^e	mixity parameter
G_m, υ_m	shear modulus and Poisson's ratio of material m	ε	bi-material constant
$r_c^{(m)}$	critical distance in material m	F	applied load
$\sigma_c^{(m)}$	tensile strength of material m	ϕ	loading angle
$K_{IC}^{(m)}$	fracture toughness of material m	L	characteristic length
$\sigma_{rr}^{(m)}, \sigma_{\theta\theta}^{(m)}, \tau_{r\theta}^{(m)}$	stress components in polar coordinates	K_{eff}	effective stress intensity factor
$f_{ij\_k}^{(m)}$	non-dimensional functions related to material m ($i, j = r, \theta$), $k = 1, 2$	η_I and η_{II}	normalized stress intensity factor
		Q, $S^{(m)}$, $R^{(m)}$, ω	known functions in terms of elastic property of the materials

case of bi-material cracks, Li and Xu [25] studied the variation of T-stress, before and after fracture initiation, for kinked bi-material cracks. Nevertheless, a stress based fracture criterion for bi-material cracks considering the effect of T-stress as well as the stress intensity factors has not been presented yet.

This paper represents a modified MTS (MMTS) criterion for prediction of fracture initiation conditions in bi-material cracks using the maximum tangential stress concept. First, the effect of T-stress on mixed mode fracture toughness of bi-material cracks is studied analytically. It is shown that the T-stress significantly influence on the estimation of mixed mode fracture toughness especially when K_I approaches zero. The MMTS criterion is proposed and the modified mixed mode fracture toughness is developed considering the effect of T-stress. The proposed criterion is then validated using the experimental results reported in the literature for Al/epoxy bi-material Brazil-nut sandwich specimens. The MMTS predictions are also compared with the conventional MTS criterion. It is shown that the MMTS criterion provides more accurate prediction of experimental data, for mixed mode fracture toughness of bi-material cracks, than conventional MTS criterion.

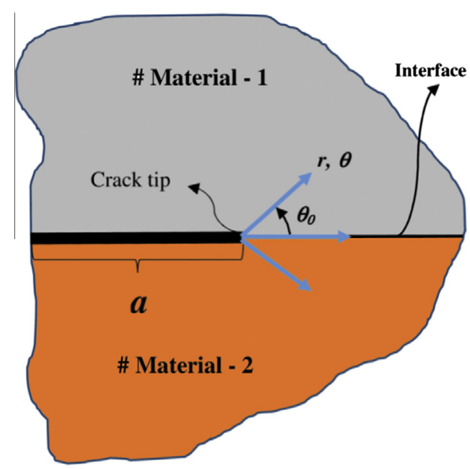

Fig. 1. General configuration of an interface crack with three possible fracture paths.

2. Elastic stress field in the vicinity of a bi-material crack tip

Fig. 1 illustrates a typical bi-material crack existing between two isotropic elastic solids with three possible fracture paths. The elastic stress field around a bi-material crack tip can be represented as [26]:

$$
\begin{aligned}
\sigma_{rr}^{(m)} &= \frac{K_I}{\sqrt{2\pi r}} f_{rr\_1}^{(m)}\left(\ln\left[\frac{r}{L}\right], \varepsilon, \theta\right) + \frac{K_{II}}{\sqrt{2\pi r}} f_{rr\_2}^{(m)}\left(\ln\left[\frac{r}{L}\right], \varepsilon, \theta\right) \\
&\quad + 4\frac{T}{R^{(m)}}\cos^2(\theta) + H.O.T \\
\sigma_{\theta\theta}^{(m)} &= \frac{K_I}{\sqrt{2\pi r}} f_{\theta\theta\_1}^{(m)}\left(\ln\left[\frac{r}{L}\right], \varepsilon, \theta\right) + \frac{K_{II}}{\sqrt{2\pi r}} f_{\theta\theta\_2}^{(m)}\left(\ln\left[\frac{r}{L}\right], \varepsilon, \theta\right) \\
&\quad + 4\frac{T}{R^{(m)}}\sin^2(\theta) + H.O.T \\
\tau_{r\theta}^{(m)} &= \frac{K_I}{\sqrt{2\pi r}} f_{r\theta\_1}^{(m)}\left(\ln\left[\frac{r}{L}\right], \varepsilon, \theta\right) + \frac{K_{II}}{\sqrt{2\pi r}} f_{r\theta\_2}^{(m)}\left(\ln\left[\frac{r}{L}\right], \varepsilon, \theta\right) \\
&\quad - 4\frac{T}{R^{(m)}}\sin(\theta)\cos(\theta) + H.O.T
\end{aligned}
\tag{1}
$$

where $R^{(m)}$ is the material parameter given in Appendix A, $m = 1,2$ denotes material number, and $(i,j) \equiv (r,\theta)$ are the polar coordinates with the origin at the bi-material crack tip. The parameter L is characteristic length and could be considered as crack length. The coefficients K_I and K_{II} and T are stress intensity factors, associated with opening (mode I) and sliding deformation (mode II), and T-stress respectively. The bi-material constant ε which represents the combination of materials at the interface is also given as

$$
\varepsilon = \frac{1}{2\pi}\ln\left(\frac{G_2\kappa_1 + G_1}{G_1\kappa_2 + G_2}\right) \tag{2}
$$

where G_m is shear modulus and the Kolosov constant κ_m equals $3-4\upsilon_m$ for plane strain condition and $(3-\upsilon_m)/(1+\upsilon_m)$ for plan stress condition (υ_m ispoison's ratio). Also, the parameters f_{rr}, $f_{\theta\theta}$ and $f_{r\theta}$ in Eq. (1) are known functions of combination of materials and geometry. The stress field components are given in Appendix A in terms of series expansion.

3. Tangential stress based criteria

This section is dedicated to introduce the MTS and MMTS criteria for determining the fracture initiation conditions at the bi-material crack tip using the elastic stress field described in the previous section.

3.1. Conventional MTS criterion

A crack at the interface can grow in three different paths as shown in Fig. 1. In general, the bi-material cracks are subjected to mixed mode deformation, even in symmetric loading condition,