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Interfacial fracture criteria based on the nominal deformation energy of interface

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ABSTRACT

A nominal strain energy density of interface has been introduced to represent the deformation state of interface. By assuming that there are deformation capacities for volume and distortional deformation energy of interface, the interfacial fracture criterion for an interface crack and the interfacial debonding criterion for a perfect bonded interface have been developed. Both these two interfacial fracture criteria agree well with experimental results. It is found that two interfacial toughness properties, K_{1C} and K_{2C}, are enough to characterize the fracture behaviors of an interface, and two interfacial strength properties, σ_C and τ_C, are enough to characterize the strength behaviors of an interface. The theory also indicated that the discontinuous stress components parallel to the interface may also affect debonding.

1. Introduction

Fracture along the interface is the most common failure mode of bonded dissimilar materials. Interfacial failure includes the fracture induced by an interface crack (the problem of interfacial toughness) and the debonding of a perfect interface induced by interfacial stresses (the problem of interfacial strength) [1–7]. There are a huge amount of studies on interface crack [8–12]. An interface crack may kink out of the interface. When it is kinked, the problem becomes the fracture of the composed material. He and Hutchinson [13] proposed a fracture criterion based on the maximum energy release rate theory, Yuuki and Xu [14] presented a criterion based on the maximum tangential stress theory. However, for an interface crack fracturing along the interface, the fracture criterion is still not very clear. Sun and Jih [15] deduced the energy release rate of an interface crack propagating along the interface. Due to the oscillatory singularity, the stress distribution at the front of an interface crack should be described simultaneously by two stress intensity factors, K_1 and K_2, for in-plane problems. However, K_1 does not correspond to normal stress only, and K_2 does not correspond to shear stress only, they are interacted in each stress component. By assuming that there exists a critical value of energy release rate, it is easy and seems reasonable to obtain the fracture criterion as $K_1^2 + K_2^2 = K_C^2$ (K_C is the critical value corresponding to the toughness of interface). However, experimental results shown that K_C is not a constant, it is dependent on the mode ratio K_2/K_1 [16,17]. This fact indicates that one have to prepare a property curve of $K_C(K_2/K_1)$, not only some material constants, for engineering applications by this approach. It seems somewhat inconvenient, thereby, the more convenient empirical elliptical fracture criterion $(K_1/K_{1C})^2 + (K_2/K_{2C})^2 = 1$, which can well describe the experimental results for many combinations, has also been proposed [18]. However, this simple criterion is only the fitting result of experiments, i.e., it is only an empirical one without any theoretical foundation. Cohesive model [19,20] is another approach mainly used in the simulation of interfacial debonding, in which both the normal and shear stress/deformation relationships should be pre-assumed. However, the cohesive model cannot provide a fracture criterion. In fact, it has to pre-assume a criterion for combined normal and shear stress state to carry out the simulation. Moreover, only the tractions on interface have been taken into account in the cohesive model, so the effect of discontinuous stress components, which are parallel to the interface, cannot be considered.

On the other hand, for the debonding of a perfect interface, various experimental methods have been developed to characterize the interface strength [21,22]. To the authors' opinion, the failure criteria for the case with compressive normal interfacial stress and the case with tensile normal interfacial stress should be different. This paper focused on the case with tensile normal interfacial stress. A nominal strain energy density of interface has been introduced to represent the deformation state of interface with its thickness being neglected. The main idea is dividing the nominal

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strain energy into volume and distortional deformation energy, and assuming that there are ultimate capacities of an interface respectively. Though such a division is a very traditional method, the idea that volume part should also be considered in interfacial fracture is innovative. The reason is that the mismatch of deformation on interface can also lead to interfacial failure, while the nominal volume strain energy is an indirect expression of the mismatch. It is the mismatch of deformation, which never appeared in a homogenous, making the interfacial fracture criterion very special.

2. The nominal strain energy density and hypothesis on interfacial fracture

An interface may physically have a very complicate microstructure, and there may even be an interfacial layer between two bonded materials. However, the interface layer or microstructure usually can be neglected in mechanical analysis for the simplicity, that is, can be modeled as a plane with zero thickness. Since the thickness of interfacial layer has been neglected, strictly, strain energy density cannot be defined for an interface itself. But it is possible to define a strain energy density for the volume containing the interface inside (called as nominal strain energy density below for the simplicity). Obviously, this nominal strain energy density is not the true one of interfacial layer itself, but it can be understood as the external loadings to the interfacial layer, though it has been neglected in the model. This fact means that the true strain energy density of interfacial layer should have a certain relationship with the nominal one. In other words, the strain energy density of interfacial layer can be expressed indirectly by the nominal one, so the interfacial fracture criterion can be developed just based on this nominal strain energy density instead of the true one.

It is well known that some stress and strain components are discontinuous at the interface. By setting the Z-axis normal to the interface, as shown in Fig. 1(a), the continuous conditions can be expressed as

$$\begin{cases} \sigma_{z1}=\sigma_{z2}=\sigma_z,\ \tau_{xz1}=\tau_{xz2}=\tau_{xz},\ \tau_{yz1}=\tau_{yz2}=\tau_{yz} \\ u_1(x,y,0)=u_2(x,y,0),\ v_1(x,y,0)=v_2(x,y,0), \\ w_1(x,y,0)=w_2(x,y,0) \end{cases} \tag{1}$$

while the stress components σ_x, σ_y and τ_{xy} are discontinuous, but they are not independent due to the constrictions of Eq. (1). They should satisfy

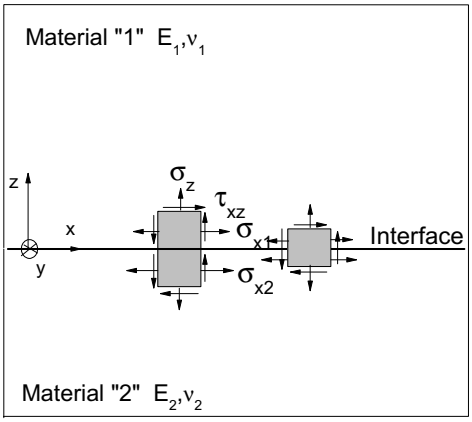
$$\begin{cases} \frac{\sigma_{x1}}{E_1}-\frac{v_1}{E_1}(\sigma_{y1}+\sigma_z)=\frac{\sigma_{x2}}{E_2}-\frac{v_2}{E_2}(\sigma_{y2}+\sigma_z) \\ \frac{\sigma_{y1}}{E_1}-\frac{v_1}{E_1}(\sigma_{x1}+\sigma_z)=\frac{\sigma_{y2}}{E_2}-\frac{v_2}{E_2}(\sigma_{x2}+\sigma_z) \\ \frac{\tau_{xy1}}{\mu_1}=\frac{\tau_{xy2}}{\mu_2} \end{cases} \tag{2}$$

here E_i, v_i, μ_i are Young's modulus, Poisson's ratio and shear modulus, respectively. Such a discontinuity may lead to the difficulty of defining the strain energy density on the interface. Considering a volume which contains the interface inside, the nominal strain energy density can then be defined as

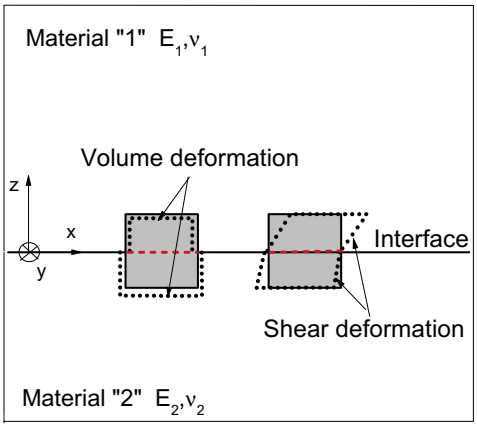
$$W=\frac{1}{2}\left[\frac{1}{2}\sigma_{ij1}\varepsilon_{ij1}+\frac{1}{2}\sigma_{ij2}\varepsilon_{ij2}\right] \tag{3}$$

This total nominal strain energy can be divided into two parts, i.e., the volume deformation part W_N and the distortional deformation part W_S, as shown in Fig. 1(b).

$$\begin{cases} W=W_N+W_S \\ W_N=\frac{1-2v_1}{12E_1}(\sigma_{x1}+\sigma_{y1}+\sigma_z)^2+\frac{1-2v_2}{12E_2}(\sigma_{x2}+\sigma_{y2}+\sigma_z)^2 \\ W_S=\frac{1+v_1}{12E_1}\left[(\sigma_{x1}-\sigma_{y1})^2+(\sigma_{y1}-\sigma_z)^2+(\sigma_{x1}-\sigma_z)^2+6\left(\tau_{xz}^2+\tau_{yz}^2+\tau_{xy1}^2\right)\right] \\ \qquad +\frac{1+v_2}{12E_2}\left[(\sigma_{x2}-\sigma_{y2})^2+(\sigma_{y2}-\sigma_z)^2+(\sigma_{x2}-\sigma_z)^2+6\left(\tau_{xz}^2+\tau_{yz}^2+\tau_{xy2}^2\right)\right] \end{cases} \tag{4}$$



(a) Discontinuity on the interface.



(b) Distinguishing of deformation energy.

Fig. 1. Stress state and deformations on the interface.

In above definition of nominal strain energy density, two subvolumes belonging to bonded materials have been introduced. But they are introduced to define only the nominal strain energy density which is used as the indirect expression of interface's deformation energy, and only the interfacial fracture is concerned in this study, so the strength or toughness behaviors of bonded materials are not necessary to be considered in interfacial fracture criterion.

Unlike that in a homogenous, both these two deformation energy parts, not only the distortional part, but also the volume part, can lead to the interfacial failure due to the mismatch at the two side of interface as shown in Fig. 1(b). To establish interfacial failure criterion, the volume deformation energy has to be considered too.

Assuming that there are critical deformation capacities W_{NC} and W_{SC} for nominal volume and distortional deformation energy, respectively, the fracture condition of an interface can then be simply assumed as

$$\frac{W_N}{W_{NC}}+\frac{W_S}{W_{SC}}=1 \tag{5}$$

It is noted that the fracture condition can also be assumed in a more complicate form than Eq. (5), but this linear form is the most simple and convenient one. Moreover, if the nominal volume and distortional energy are considered as parameters representing the damage induced by loadings, Eq. (5) agrees with the linear damage accumulation law. But its validity, of course, should be examined by experimental results carefully.