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Mixed-mode I+II continuum damage model applied to fracture characterization of bonded joints

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ABSTRACT

A continuum mixed-mode I+II damage model allowing simulation of damage initiation and propagation in adhesive bonded joints is presented. The model is based on a stress criterion to identify damage onset and a fracture mechanics criterion to simulate gradual degradation of stiffness during loading. It is implemented in two-dimensional solid elements thus allowing identifying the volumetric shape of damaged regions in the vicinity of the crack tip. Additionally, the model is able to predict crack kinking which occurs as a function of the used criteria. The application of the proposed methodology in the context of pure modes (I and II) fracture characterization tests of bonded joints provide the evaluation of the influence of asymmetric propagation on the measured fracture energies. This phenomenon becomes more relevant with the increase of adhesive thickness.

1. Introduction

The use of adhesive joints in critical structures has been increasing due to several advantages intrinsic to this joining method. As a consequence, more demanding design methods are required in order to deal with several details influencing bonded joint mechanical behavior that are not accounted for in classical approaches. In the strength of materials based approaches the maximum stress or strain criteria are the most popular ones [1–4]. They are based on the assumption that failure occurs when one of the stress or strain tensor components attains the respective strength value. The referred criteria have a main difficulty when applied to the failure prediction of bonded joints. In fact, bonded joints with sharp corners are characterized by stress singularities at the end of overlapping regions. In order to overcome these drawbacks, the use of cohesive zone models (CZM) in fracture problems has become frequent in the most recent years. One of the most important advantages of cohesive models is related to its capacity to simulate onset and non-self-similar growth of damage. They are based on a softening relationship between stresses and relative displacements between crack faces, thus simulating a gradual degradation of material properties. Generally, stress based and energetic fracture mechanics criteria are used to simulate damage onset and propagation, respectively. Cohesive damage models are usually based on interface finite elements [5–7] connecting plane or three-dimensional solid elements. Those elements are placed at the planes where damage is prone to occur but, in several cases, these critical regions can be difficult to identify in advance. Additionally, the application of CZM in the context of bonded joints frequently neglects adhesive thickness [7–9], thus not being able to capture the influence of asymmetrical propagation and crack different paths along adhesive thickness. Moreover, the referred approaches do not allow the simulation of adherends constraint on the fracture process zone development inside the adhesive. On the other hand, it is known that crack propagation in bonded joints often occurs under mixed-mode I+II loading. In fact, typical applications of bonded joints frequently develop shear and peel stresses in critical regions. Furthermore, it is known that even in problems where one of the modes predominates, there is some mode-mixity that can influence the measured fracture energy. An example occurs when the double cantilever beam test is used to measure fracture energy under mode I loading. Since the crack can propagate near to an interface owing to stress concentrations induced by mismatch properties between adherends and adhesive [10,11] a geometrical asymmetry takes place. Depending on the adhesive thickness and material properties of the joint components (adherends and adhesive) a non-negligible mode II loading component can arise. This statement reinforces the need to develop accurate numerical methods accounting for mixed-mode I+II crack growth in bonded joints.

In order to overcome the referred drawbacks a continuum mixed-mode I+II damage model is proposed. The model is implemented in two dimensional solid elements and combines stress and fracture based criteria to deal with damage onset and growth. The main advantage inherent to the proposed approach is

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its capacity to simulate volumetric damage and crack different paths inside the adhesive thus reflecting the better experimental reality. The size of the fracture process zone (FPZ) which is the region in the vicinity of the crack tip where plasticity, micro-cracking and other various damage mechanisms take place plays an important role. These aspects become more relevant when ductile adhesives are considered since in these cases the FPZ can be very large. Consequently, the accurate simulation of the FPZ is fundamental in order to perform reliable fracture characterization of adhesives.

2. Damage model

The proposed damage model is based on the assumption that damage evolution reflects on stiffness decrease. The model is implemented via UMAT subroutine in the ABAQUS Standard® software. The goal is to include a damage softening law in two-dimensional solid elements used to simulate the adhesive behavior. In the considered bilinear pure-mode law (Fig. 1) damage starts when local strength ($\sigma_{u,i}$, i=I, II) is attained and its propagation is dictated by the respective fracture energy ($G_{i,c}$)

$$G_{i,c} = \frac{\sigma_{u,i}\varepsilon_{u,i}l_c}{2} \tag{1}$$

being l_c a characteristic length that allows establishing the relationship between opening (δ_I) or shear (δ_{II}) displacements into the corresponding strain (ε_i, i=I, II). This parameter represents the length of influence of a given integration point and physically can be viewed as being the dimension in which the material behaves homogeneously [12]. Considering a pure-mode damage model and isotropic damage, the stress–strain relationship during softening becomes

$$\sigma = (1-d_i)\mathbf{C}\boldsymbol{\varepsilon} \tag{2}$$

in which $\mathbf{C}$ is the linear elastic stiffness matrix and d_i is a scalar representing the damage parameter in the pure mode i (i=I, II). This parameter can be easily obtained from the second branch of the damage model (Fig. 1)

$$d_i = \frac{\delta_{u,i}(\delta_i-\delta_{o,i})}{\delta_i(\delta_{u,i}-\delta_{o,i})} \tag{3}$$

where δ_i, $\delta_{o,i}$ and $\delta_{u,i}$ represent the current, onset and ultimate displacements, respectively. The damage parameter varies between zero (undamaged material) and unity (complete material failure). More details about the continuum pure-mode damage model can be found in [12].

The mixed-mode I+II continuum damage model proposed in this work can be viewed as an extension of the referred pure-mode model. The main idea is to use a stress based criterion to detect damage initiation and a fracture based criterion to simulate damage propagation. The quadratic stress criterion was considered to simulate the damage onset

$$\left(\frac{\sigma_I}{\sigma_u}\right)^2 + \left(\frac{\sigma_{II}}{\sigma_u}\right)^2 + \left(\frac{\tau}{\tau_u}\right)^2 = 1 \tag{4}$$

being σ_I, σ_{II} the normal and τ the shear stresses (Fig. 2), and σ_u,τ_u are the corresponding ultimate values. σ_{II} is the normal stress parallel to crack direction and is usually known as the T-stress component. Several authors have demonstrated that T-stresses play an important role in which concerns crack growth under mixed-mode loading [13] and on the size and shape of the plastic zone [14]. It is also assumed that under compressive stresses in direction I, both normal components (σ_I, σ_{II}) do not contribute to damage. In this case, a pure mode problem is considered assuming a pure mode II loading. Considering the ratios

$$\alpha_s = \frac{\sigma_{II}}{\sigma_I} \quad ; \quad \beta_s = \frac{|\tau|}{\sigma_I} \tag{5}$$

in Eq. (4), the mode I stress component leading to damage onset (σ_{eI}) under mixed-mode loading can be defined as follows:

$$\sigma_{eI} = \frac{\sigma_u\tau_u}{\sqrt{\tau_u^2(1+\alpha_s^2)+\beta_s^2\sigma_u^2}} \tag{6}$$

Since the damage parameter is defined as function of displacements (Eq. (3)), it is necessary to define the displacement components in each mode ($\delta_{o,Im}$ and $\delta_{o,IIm}$) corresponding to damage initiation. From Hooke's law

$$\delta_{o,Im} = \frac{\sigma_{eI}}{E}(1-\nu\alpha_s)l_c$$
$$\delta_{o,IIm} = \frac{2\sigma_{eI}(1+\nu)}{E}\beta_s l_c \tag{7}$$

being E and ν the elastic modulus and Poisson's ratio, respectively. The equivalent displacement at damage onset is given by

$$\delta_{o,m} = \sqrt{\delta_{o,Im}^2+\delta_{o,IIm}^2} = \frac{\sigma_{eI}}{E}\sqrt{(1-\nu\alpha_s)^2+4\beta_s^2(1+\nu)^2}l_c \tag{8}$$

Damage propagation is simulated by means of the linear energetic fracture criterion

$$\frac{G_I}{G_{Ic}} + \frac{G_{II}}{G_{IIc}} = 1 \tag{9}$$

The energy components are given by

$$G_I = \frac{\sigma_{eI}\delta_{u,Im}}{2} \quad ; \quad G_{II} = \frac{|\tau|\delta_{u,IIm}}{2} \tag{10}$$

where $\delta_{u,Im}$ and $\delta_{u,IIm}$ represent the ultimate displacements in each mode leading to failure under mixed-mode I+II loading.

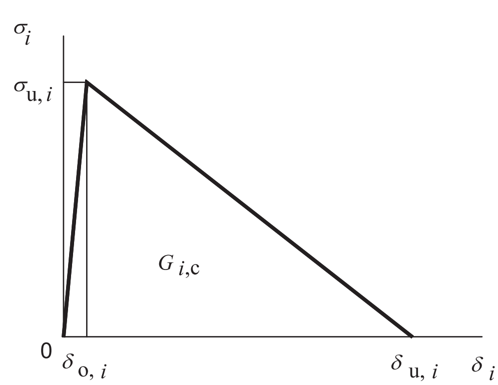

Fig. 1. Bilinear pure mode law.

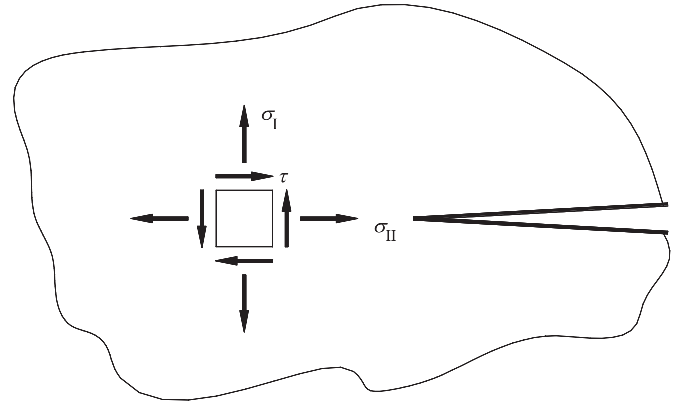

Fig. 2. Stress components in the vicinity of the crack tip inside adhesive layer.