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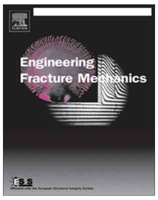

Comparison between models based on a coupled criterion for the prediction of the failure of adhesively bonded joints

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ABSTRACT

This article is aimed at comparing two models based on the same assumptions to analyze the failure of adhesively bonded joints. These models combine the use of two criteria: a stress criterion for the initiation of micro-cracks and an energy criterion for the propagation of these micro-cracks to create a macro-crack. The first model only requires elastic calculations but the second is a continuum damage model. It is shown that the comparison of the two models against experimental results permits to describe in a correct manner the effect of geometrical parameters on the strength of a bonded joint.

1. Introduction

Due to their high specific properties composite materials are more and more used in various industrial applications such as aeronautic, automotive or renewable marine energy systems. These applications necessitate the assembly of composite parts in order to transfer loads to other composite or metallic parts. The use of mechanical joints introduces some stress singularities in the composite that reduce drastically its load capabilities [1]. This is the reason why adhesively bonded joints appear to be a good approach to assemble composite materials. Indeed, the adhesive bonding method ensures light but resistant structures. Moreover, bonded joints enable the stress concentrations generated by mechanical assembly techniques to be reduced [2]. However, in order to attain sufficient confidence in the design of bonded structures, it is necessary to develop models that allow predicting the strength of the assembly during the very early design of the structure. In order to attain this goal, different approaches have been proposed in the literature. These methods could be separated into two categories: stress or energy based approaches with an elastic model. In energy based approach, rupture is assumed to occur when a pre-existing crack extends provided enough energy is available [3,4] leading to a net decrease in the stored potential energy of the loaded system. The propagation of the crack is possible if the change in potential energy with the crack area (the energy release rate) is greater than the critical strain energy release rate or fracture toughness. In stress-based approaches, failure occurs if the stress is greater than a critical value (see [5] for a review of different criteria). Stress based criteria are no more valid near a stress singularity. Indeed, in this case, it is necessary to introduce an internal length in the failure criterion: the stress criterion is applied at a given distance of the singularity (point stress criterion [6]) or the stress used in the criterion is averaged along a distance (average stress criterion [7]). A review of these methods applied to adhesively bonded joints

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Nomenclature for the finite fracture approach

$A(d)$	normalized incremental energy release rate
β, r^{σ}	mode mixity and ratio of multiaxiallity of the stress for the finite fracture approach
ΔW	change in potential energy
$\varepsilon^{c}_{\text{energy}}, \varepsilon^{c}_{stress}$	strain at failure predicted by the energy and the stress criteria
${F_1}^{a}$ and ${F_3}^{a}$	force in direction 1 and 3 that permit to maintain the crack closed at the coordinate a for the MVCCT
$G^{\text{Inc.}}(d)$	incremental energy release
$k(x)$	dimensionless parameter for the stress
$({U_1}^{b}$ and ${U_3}^{b})$ $({U_1}^{c}$ and ${U_3}^{c})$	nodal displacements at the upper crack and the nodal displacements at the upper crack face for the MVCCT

Nomenclature for the Damage Model

$\underline{\underline{C}}^{0}, \underline{\underline{\tilde{C}}}$	initial and damaged elastic stiffness of the adhesive
δ, δ_0, δ_c	equivalent strain, equivalent strain corresponding to the onset of damage and equivalent strain corresponding to the failure of the element
$\underline{\overline{\varepsilon}}$	strain driving the damage
L^{e}, w^{e}, t^{e}	length, width and thickness of the element
S_0, S'	surface element in the plane (1, 2) and surface of the crack in the element
$\underline{\underline{H}}$	tensor of the effect of the damage
$\underline{\sigma}_0^{*}$	stress corresponding to the onset of the damage
τ, τ^{0}	equivalent stress and equivalent stress corresponding to the onset of the damage
θ, γ	ratio of multiaxiallity of the stress and the strain for the damage model
ρ	damage variable

General notations

d	crack length
E_{ii}, G_{ij}	Young modulus in direction i and shear modulus in the direction ij
E, ν	Young modulus and Poisson's ratio
G, G_1 and G_2	total energy release rate, energy release rate in mode I and II
G^{c}, G^{c}_{1}, G^{c}_{2}	total critical energy release rate, mode I and mode II critical energy release rate
h	thickness of the joint
l_s, l_{overlap}, w, t_a	geometry of the single lap joint specimen: length of the substrate, overlap length, width and thickness of the adhesive
Z_t and S_c	the peel and out-of-plane shear strengths
X_{ij} or $(\underline{X})_{ij}$	component ij of the second order tensor X

is proposed in [8]. Whether with the energy criterion or with the stress-based criterion, an artificial internal length is introduced: the length of the pre-crack for the energy-based criterion or the length of the internal length used in stress-based criterion. This internal length must be determined using experimental tests and is a function of numerous parameters including the material properties and the geometry. This kind of approach cannot be used in an optimization loop or to predict the evolution of the failure load over time (due to aging, for example).

In order to overcome this problem, it has been shown in [9] that it is necessary to combine a stress and an energy criteria. The energy condition provides a lower bound of the admissible crack increments while the stress criterion provides an upper bound. At a physical point of view, the stress criterion permits to insure that the stress is high enough to create micro-cracks while the energetic criterion states that the energy release rate is high enough to propagate these micro-cracks on a given length to create a macroscopic crack. Coupling these two conditions allows determining the nucleation length and the corresponding failure load. Contrary to the point stress or to the fracture mechanics approaches, it is not necessary to postulate or identify this length. This approach has been applied successfully to describe the failure due to a delamination initiated from an edge in laminate composites [10] or the failure of an open-hole in composites in tension [11,12] or compression [13]. It has also been recently applied to describe the effect of the adhesive thickness on the failure of adhesively bonded joints [14,15] or the debonding between an inclusion and the matrix [16]. All these studies validate the use of a coupled strength and energy criterion for the prediction of crack initiation.

Rather similar approaches are used in models relying on damage mechanics. Indeed, a damage model is usually defined by a threshold and by the kinetic of the damage. A stress criterion describes the initiation of the damage while an energy criterion drives its propagation. The damage model could be applied through cohesive zone or continuum damage mechanics formulations. The use of cohesive zone approach to describe the failure of interface between two plies in composite materials or between two substrates in adhesively bonded specimens has become common these last few years since those