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Cohesive/adhesive failure interaction in ductile adhesive joints Part I: A smeared-crack model for cohesive failure

Jonathan P.-H. Belnoue *, Stephen R. Hallett

Advanced Composite Centre for Innovation and Science (ACCIS), University of Bristol, Queen's Building, University Walk, Bristol BS8 1TR, UK

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ABSTRACT

This paper proposes a new methodology for the finite element (FE) modelling of failure in adhesively bonded joint. Unlike current methods, cohesive and adhesive failures are treated separately. Initial results show the method's ability to give accurate prediction of failure of adhesive joints subjected to thickness-induced constraint and complex multi-axial loading using a single set of material parameters. The present paper (part I), focuses on the development of a smeared-crack model for cohesive failure. Model verification and validation are performed comparing the model predictions with experimental data from 3 point bending End Notched Flexure (3ENF) and Double Cantilever Beam (DCB) fracture tests conducted on adhesively bonded composite panels of different adhesive thicknesses.

1. Introduction

Due to their light weight and high strength and stiffness, composite materials are becoming increasingly popular for the design of many engineering components in areas as diverse as tidal and wind energy, jet-engines, automobiles, etc. Due to the complexity of one-piece component manufacturing, the need to develop good joining techniques is becoming more pressing. As opposed to more widespread joining techniques such as bolted and rivetted joints, adhesive joints do not need holes to be machined, thus reducing the addition of high stress concentrations and the risk of component failure [1]. Furthermore, they are lighter and more economical. Historically, the difficulty to assess their integrity in a fast non-destructive way and to predict their resistance to failure accurately has been a major impediment to a more systematic use of adhesive joints in composites-based engineering components design. However, due to the combined effects of improved adhesive mechanical performance, a better understanding of the failure mechanisms involved and the increased accuracy of the numerical methods available to the designers, this has recently started to change.

The cohesive zone method (CZM) has been the main contributor to the improvement of failure predictions of adhesive joints. The method allows the simulation of damage growth by consideration of energetic principles and allows taking into account phenomena such as mixed-mode loading [2–4], rate-dependent effects [5], environmental effects [6,7] and fatigue loading [8]. The mechanical response of the adhesive can either be represented fully with the traction-opening response of the cohesive zone [9–11] (this is essentially the strategy used in the modelling of thin adhesive layers) or with a layer of cohesive elements incorporated within a bulk material made of elasto-plastic solids [12–14] (this suits best the description of failure in thick adhesive layer). In both cases, no formal distinction is made between cohesive (i.e. rupture of the adhesive bulk material) and adhesive failure (i.e. interfacial failure or debonding of the adhesive). In other words, the traction-separation law used in the cohesive elements is set such that it represents the overall behaviour of the bond which results from the interaction between cohesive and adhesive failure.

Failure in brittle adhesives can easily be modelled using a simple bi-linear traction-separation law and one single set of material parameters. On the other hand, failure mechanisms of ductile adhesives involve complex multi-axial plastic deformations. These can be responsible for up to 80% of the load carrying capacity of common structural adhesives [15] and can result in the non-monotonic dependency of bond toughness and strength with joint geometry [16]. In such a case, accurate failure predictions necessitate varying the traction-separation law parameters [14] and shape [17] with the bond dimensions. As a result, full characterisation of a ductile adhesive can be both costly and time consuming. This is particularly the case since adhesive joint behaviour can also depend on hydrostatic pressure [18,19], adding an extra level of complexity. Finally as pointed out in [14], the method assumes the crack path *a-priori*. As the position of the

* Corresponding author.
E-mail address: jonathan.belnoue@bristol.ac.uk (J.-H. Belnoue).

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crack path in the layer affects the plastic strain distribution the contribution due to plastic yielding in the adhesive (which, in return, acts upon the traction-separation law definition) is an additional potential source of inaccuracy of the state-of-the-art modelling technique of adhesively bonded joints.

Here, a new methodology whereby cohesive and adhesive failures are treated separately is proposed. The adhesive deformation (i.e. cohesive failure) is modelled via a smeared-crack approach which allows crack propagation without knowing the crack path in advance and which can easily be used to model phenomena where plasticity and damage coexist [20]. Preliminary analytical calculations (using the method described in [21,22]) and CZM-based finite element analysis (that follows the method described in [14]) made for the predictions of the failure load of the double-lap joint specimens presented in a companion paper [23] suggested that the adhesive plasticity and its dependence to hydrostatic pressure [18,19,24,25] play a key role in the failure mechanisms of the structural adhesive used in the present study. Based on these observations, the adhesive plasticity is taken into account through the use of a pressure-dependent yield criterion. Adhesive failure, on the other hand, is modelled by inserting a layer of cohesive elements at the interface between the adhesive and the adherends. The present paper (part I) focuses on the formulation of a new model for cohesive failure. Particular attention is given to the influence of the bondline thickness and loading mode on the joint apparent toughness. In the companion paper [23], the proposed methodology is applied to the modelling of a double lap-joint specimen with dissimilar adherends and the interaction between cohesive and adhesive failure is studied in more detail.

2. Model formulation

Both continuum damage mechanics (CDM) and cohesive zone modelling make use of history variable that tracks the extent of damage accumulated on the crack plane. d is a damage parameter whose initial value is $d^0 = 0$ and that remains zero until the damage initiation condition is met. It is a monotonically increasing value, which reaches the failure value 1 when the crack faces fully separate. In CDM, the evolution of d is closely tight to the evolution of the strain $\boldsymbol{\varepsilon}$ at the material point under consideration. Whilst in cohesive zone modelling, the variation of d is dictated by the shape of the traction-separation law. The smeared crack model approach [20,26] used here allows to relate the damage variable d traditionally used in CDM, to the damage variable that would be used to describe an equivalent traction-separation law within a cohesive zone modelling framework.

Smeared-crack models are based on the decomposition (see Eq. (1)) of the total strain tensor ($\boldsymbol{\varepsilon}$) into the sum of a part solely due to the material deformation ($\boldsymbol{\varepsilon^e} + \boldsymbol{\varepsilon^p}$) and another term,$\boldsymbol{\varepsilon^c}$, accounting for the cracking contribution.

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon^e} + \boldsymbol{\varepsilon^p} + \boldsymbol{\varepsilon^c} \tag{1}$$

In Eq. (1), the part of the total strain tensor due to the material deformation is additively split into an elastic term (ε^e) and a plastic term (ε^p). The additive splitting of the strain used here implies some limitation on the validity of the model concerning large strains. Giving the relatively large strains observed in the adhesive studied (see Fig. 2 for example), this is an evident limitation of the proposed approach. However, due to the complexity of the physical phenomena considered, some simplifications had to be made. The adaptation of the model to a large-deformation framework could possibly be implemented in future. It is also worth noting that this approach is consistent with the small strain assumptions made by a number of other contributions in the literature investigating the failure of ductile adhesive bonds (e.g. [9,14]).

Here, 8 noded brick elements are used. The material degradation is triggered when the plastic strain exceeds a certain threshold. The evolution of a damage parameter (d) is determined from energetic principles via a traction-separation law. d controls the norm of an anisotropic second-order damage tensor, $\mathbf{D}$, that allows the localisation of damage into a plane.

2.1. Plastic deformation

The aim of the present contribution is to set a new methodology for failure prediction in adhesive joints and to gain understanding of the way the adhesive plasticity, cohesive and adhesive failure interact with each other.[1] Hence a very pragmatic approach is taken. Prior to degradation, the influence of hydrostatic pressure on the development of plasticity in the adhesive was modelled through a simple linear Drucker–Prager (D.P.) yield criterion (see Eq. (2)).

$$\psi = \sigma^{VM} + \eta\sigma_H - \xi c = 0 \tag{2}$$

σ^{VM} and σ_H are the Von Mises stress and hydrostatic pressure respectively. ξ, c and η are parameters that can be expressed as a function of the adhesive's yield stresses in pure tension (σ_T) and in pure compression (σ_C).

The evolution equation for the plastic strain is:

$$\dot{\boldsymbol{\varepsilon}}^p = \dot{\gamma}\frac{\partial\psi}{\partial\boldsymbol{\sigma}} = \dot{\gamma}\boldsymbol{n} \tag{3}$$

with $\boldsymbol{n}$ being the direction of the plastic flow and $\dot{\gamma}$ the plastic multiplier. Inserting Eq. (3) into the Hooke's law and using the additive splitting describe in Eq. (1) ($\boldsymbol{\varepsilon^c}$ is assumed to be null at the moment) gives rise to:

$$\dot{\boldsymbol{\sigma}} = \mathbb{C}_e : (\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^p) = \mathbb{C}_e : (\dot{\boldsymbol{\varepsilon}} - \dot{\gamma}\boldsymbol{n}) \tag{4}$$

where $\mathbb{C}_e$ is the elasticity tensor. The evolution equation for the equivalent plastic strain is then given by:

$$\dot{\varepsilon}^p_{eq} = \sqrt{\frac{2}{3}\dot{\boldsymbol{\varepsilon}}^p : \dot{\boldsymbol{\varepsilon}}^p} = \sqrt{\frac{2}{3}}\|\dot{\boldsymbol{\varepsilon}}^p\| = \sqrt{\frac{2}{3}}\dot{\gamma}\|\boldsymbol{n}\| \tag{5}$$

The loading and unloading conditions are given by the Kuhn–Tucker equations:

$$\dot{\gamma} \geq 0;\ \psi \leq 0;\ \psi\dot{\gamma} = 0 \tag{6}$$

In case of plastic loading $\dot{\gamma} > 0$ and $\psi = 0$ holds whilst in the case of unloading, $\dot{\gamma} = 0$ and $\psi < 0$. This can be summarized with the consistency condition:

$$\dot{\psi}\dot{\gamma} = 0 \tag{7}$$

In the case when yielding occurs, $\dot{\gamma}$ can be obtained from the consistency condition:

$$\dot{\psi} = \frac{\partial\psi}{\partial\boldsymbol{\sigma}} : \dot{\boldsymbol{\sigma}} + \frac{\partial\psi}{\partial\varepsilon^p_{eq}}\dot{\varepsilon}^p_{eq} = 0 \tag{8}$$

which using (Eqs. (4) and 5) can be rearranged as:

$$\dot{\psi} = \boldsymbol{n} : \mathbb{C}_e : (\dot{\boldsymbol{\varepsilon}} - \dot{\gamma}\boldsymbol{n}) + \frac{\partial\psi}{\partial\varepsilon^p_{eq}}\sqrt{\frac{2}{3}}\dot{\gamma}\|\boldsymbol{n}\| = 0 \tag{9}$$

[1] The interaction between cohesive and adhesive failure is addressed in the part 2 paper [23].