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Cohesive/adhesive failure interaction in ductile adhesive joints Part II: Quasi-static and fatigue analysis of double lap-joint specimens subjected to through-thickness compressive loading

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ABSTRACT

This paper proposes a new methodology for the finite element (FE) modelling of failure in adhesively bonded joints. Cohesive and adhesive failure are treated separately which allows accurate failure predictions for adhesive joints of different thicknesses using a single set of material parameters. In a companion paper (part I), a new smeared-crack model for adhesive joint cohesive failure was proposed and validated. The present contribution gives an in depth investigation into the interaction among plasticity, cohesive failure and adhesive failure, with application to structural joints. Quasi-static FE analyses of double lap-joint specimens with different thicknesses and under different levels of hydrostatic pressure were performed and compared to experimental results. In all the cases studied, the numerical analysis correctly predicts the driving mechanisms and the specimens' final failure. Accurate fatigue life predictions are made with the addition of a Paris based damage law to the interface elements used to model the adhesive failure.

1. Introduction

Recent progresses in adhesive joint technology (e.g., tougher systems and better surface preparation) [1,2] have resulted in an increased use of adhesive bonds in the design of engineering components of increased complexity, subjected to increasingly challenging mechanical loading and environment. For example, adhesive joints have now been integrated in the design of rotating engines such as tidal and wind turbines where the ability of the structural components to resist fatigue failure is of prime importance. Traditionally adhesive joints have been designed in such a way that failure cannot happen in the joint [1]. Whilst being the safest option, this results in levels overdesign and the resulting costs that are not sustainable for the industry.

In recent years, methods aiming at improving the reliability of numerical tools for fatigue failure predictions of adhesive bond have been proposed [3–10]. Like their quasi-static failure equivalent [11], these models are primarily based on the cohesive zone method (CZM). Most of these models however do not take account of the adhesive plastic deformation. This is potentially an impediment for accurate fatigue life prediction in adhesive joints involving new tougher (i.e., more ductile) systems. Fatigue failures mostly occur whilst the adhesive is in the elastic regime. Adhesive plastic deformation can however be responsible for up to 80% of the joint strength [12] and consequently has a non-negligible influence on the severity of the applied fatigue cycles.

In the "science of adhesive joints," adhesive failure is generally not accepted as it is often the result of poorly made and/or designed joints. Therefore, most adhesive joints models available in the literature tend to disregard it or, at best, lump all the fracture mechanisms together. This often gives rise to phenomenological models using material parameters whose physical nature is not always easy to understand and showing a fairly narrow range of applicability. Even though this approach works well for industry purposes, it is harder to justify from an academic point of view as it does not give much room for deeper understanding of the physical phenomena leading to the joints' failure. In the case of quasi-static failure, Pardoen and Kinloch [13–15] have performed in depth experimental and numerical analysis of the influence exerted by the joint plasticity on its overall strength. The present contribution explores in more detail the competition between adhesive and cohesive failure of ductile adhesives. Particular emphasis is placed on an industrially relevant steel to composite

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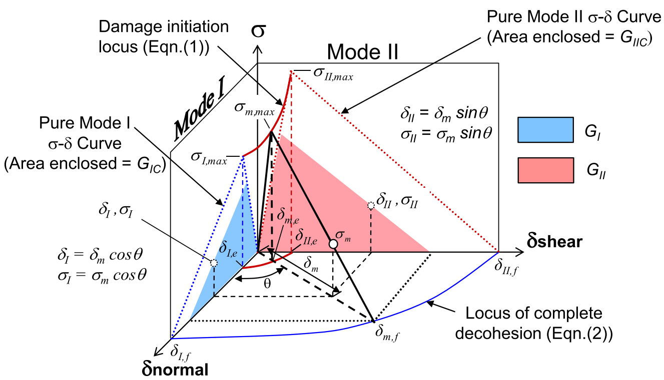

Fig. 1. The mixed-mode traction separation response [17].

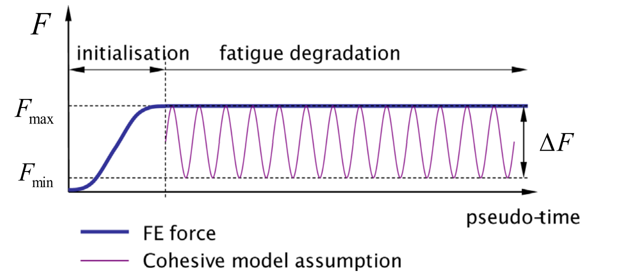

Fig. 2. Modelling the envelopes of loads and displacements in a cyclic regime.

double lap-joint specimen that fails under different modes for different levels of hydrostatic pressure and depending on whether loaded statically or cyclically. The modelling of the joint represents the adhesive with the smeared-crack model for cohesive failure presented in part I [11]. Adhesive failure is modelled through the insertion at the adhesive/composite interface of a layer of cohesive elements. Numerical analysis clearly suggests that both failure mechanisms need to be considered to predict accurately the specimen strength.

2. Adhesive failure modelling

2.1. Static loading

Interfacial failure that may arise from debonding of the adhesive was modelled using cohesive elements with a bi-linear traction–separation law [16]. Under mixed mode loading, the formulation can be illustrated using a single three-dimensional map by representing the normal opening mode (mode I) on the 0–σ–δ_{normal} plane, and the transverse shear mode (mode II) on the 0–σ–δ_{shear} plane, as shown in Fig. 1. The triangles 0–$\sigma_{I,max}$–$\delta_{I,f}$ and 0–$\sigma_{II,max}$–$\delta_{II,f}$ are the responses in pure opening mode and in pure shear mode respectively. Any point on the 0–δ_{normal} –δ_{shear} plane represents a mixed-mode relative displacement.

The mixed mode damage onset displacement, $\delta_{m,e}$, and interfacial strength, $\sigma_{m,max}$, are calculated using a quadratic damage onset criterion:

$$\left(\frac{\max(\sigma_I,0)}{\sigma_{I,max}}\right)^2+\left(\frac{\sigma_{II}}{\sigma_{II,max}}\right)^2=1 \tag{1}$$

The failure displacement corresponding to complete decohesion, $\delta_{m,f}$, is calculated from the following failure criterion:

$$\frac{G_I}{G_{IC}}+\frac{G_{II}}{G_{IIC}}=1 \tag{2}$$

where G_{IC} and G_{IIC} are the critical energy release rates for pure mode I (opening) and pure mode II (shear), respectively.

The accumulation of irreversible damage can then be tracked using the static damage parameter, d_S, defined as follows (Fig. 2):

$$d_S(\delta_m)=\frac{\delta_m-\delta_{m,e}}{\delta_{m,f}-\delta_{m,e}} \tag{3}$$

The element complete failure occurs when d_S reaches a value of unity.

A modification of the interface element formulation which takes into account the enhancement in effective mode-II properties when the interface is under through-thickness compressive stresses is used here. It is assumed that the initial cohesive stiffness and softening slope remain constant, and the effective mode-II strength is then given by

$$\sigma'^{max}_{II}=\sigma^{max}_{II}-\eta\sigma_{33} \tag{4}$$

where σ_{33} is the through-thickness stress, σ^{max}_{II} is the mode-II strength in the absence of through-thickness stresses, and η is an empirically derived enhancement factor analogous to an internal friction coefficient. The effective critical mode-II strain energy release rate becomes

$$G'_{IIC}=\left(\frac{\sigma'^{max}_{II}}{\sigma^{max}_{II}}\right)G_{IIC} \tag{5}$$

A value of $\eta=0.3$ was set. This value should ideally be measured experimentally for the specific material in use. However, this was not available and so the value used was chosen consistent with the value measured by Gan et al. [18] in the case of an epoxy-matrix composite. Cognard et al. [19] have measured the elastic limit of an epoxy adhesive in a bonded assembly under different levels of hydrostatic pressure. Fitting their data with a very simple Mohr–Coulomb criterion also leads to a value for η very close to 0.3, thus further justifying the choice of this value.

2.2. Fatigue loading

In the last few years, algorithms to include fatigue damage accumulation in the cohesive element formulation have been developed [17,20–23]. These incorporate the Paris law for crack growth, where the crack growth rate, $\frac{\partial a}{\partial N}$, is characterized with respect to the change in crack tip strain energy release rate, ΔG, within each fatigue cycle using the following relationship:

$$\frac{\partial a}{\partial N}=C\left(\frac{\Delta G}{G_C}\right)^m \tag{6}$$

The parameters C and m are constants derived by curve fitting experimental data.

For the more common case of mixed mode loading, the Paris law constants, C and m, are calculated from the, experimentally measured, pure mode I and pure mode II coefficients using a simple linear rule of mixtures between modes I and II as proposed by Russell and Street [24]:

$$C_m=C_I\left(\frac{G_I}{G_T}\right)+C_{II}\left(\frac{G_{II}}{G_T}\right)(\mathrm{a})m_m=m_I\left(\frac{G_I}{G_T}\right)+m_{II}\left(\frac{G_{II}}{G_T}\right)(\mathrm{b}) \tag{7}$$

In these equations, the subscripts m, I and II are used to distinguish between the experimentally derived mode I and mode II Paris law constants and the calculated mixed mode Paris law constants. G_T is the total strain energy release rate: $G_T=G_I+G_{II}$. More sophisticated rules such as the one described by Blanco et al. [25] could be used and may give greater accuracy. However, these rules would necessitate the experimental determination of a third (mixed-mode) point that was not available for the material system used in the present work.

In the numerical fatigue model, it would be too computationally expensive to model each fatigue cycle explicitly. An envelope