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A maximum stress at a distance criterion for the prediction of crack propagation in adhesively-bonded joints

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ABSTRACT

The present work relates to the numerical prediction of the mode I failure of metal-to-metal adhesive joints under quasi-static, steady-state conditions by means of a criterion based on attaining a critical value of the maximum principal stress at a critical distance ahead of the crack tip. The model accurately predicts the failure of three adhesives (i) over a wide range of the thickness of the adhesive layer from 0.1 to 1 mm, and (ii) for two very different test geometries: namely the linear elastic fracture-mechanics tapered double-cantilever beam test and the elastic–plastic fracture-mechanics wedge-peel test.

1. Introduction

Adhesive bonding is a very widely employed method for joining materials, often referred to as the 'adherends'. Unlike other joining methods, such as riveting, welding or the use of mechanical fasteners, it offers quite a few major advantages [1] such as (i) the ability to join dissimilar materials and (ii) the fact that it gives a more uniform stress distribution across the joint, which in turn results in an increased service-life under cyclic-fatigue loading. However, adhesive bonding is still not widely used as the sole joining method in applications where the joint is a safety–critical feature of the structure. This can be explained by the lack of well-established numerical tools and design methodologies which result in high development costs.

Therefore, the present authors have been working on gaining a better understanding of the failure of adhesive joints and on developing reliable numerical models capable of predicting accurately this failure with a minimum number of characteristic, material parameters. To reduce the scope of the task, the study is restricted, to metal-to-metal adhesive joints bonded using epoxy-based structural adhesives that fail under steady-state, mode I (or predominantly mode I) conditions and exhibit quasi-static crack growth. The model that the authors have used so far [2,3] has been derived from the work of Tvergaard and Hutchinson [4,5] and employs a cohesive zone model (CZM). The CZM represents the damage mechanisms responsible for fracture and has also been employed in modelling the failure of adhesive joints by, for example, Kafkalidis et al. [6] Yang et al. [7], Georgiou et al. [8], Ferracin [9], Pardoen et al. [10], Salomonsson and Andersson [11] and Cooper et al. [12]. In the model employed by Kafkalidis et al. [6], Yang et al. [7], Georgiou et al. [8] or Ferracin [9], the CZM represents the full thickness of the adhesive layer while, in the work of Salomonsson and Andersson [11], the polymer and the reinforcing particles are both represented by continuum finite elements that are all surrounded by interface elements, allowing for the development of micro-cracks. The approach followed by Pardoen et al. [10] and Martiny et al. [2,3] lies somewhere in

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Nomenclature

CZM	cohesive zone model
EPFM	elastic–plastic fracture mechanics
LEFM	linear-elastic fracture-mechanics
TDCB	tapered double-cantilever beam
a	crack length in the TDCB test
B	width of the TDCB test specimens
E	Young modulus
E_s	Young modulus of the adherend material
G_a	adhesive fracture energy
G_a^{ref}	reference adhesive fracture energy used to normalise the values G_a
G_a^{SSY}	adhesive fracture energy under small-scale yielding conditions
h	thickness of the adherends
h_{adh}	thickness of the adhesive layer
m	a parameter characterising the taper of the adherends in the TDCB test
n	strain-hardening exponent in the power-hardening law
P	load measured in the TDCB test
q	hardening exponent in the Swift hardening law
r_c	critical distance used in the failure criterion
r_Y	height of the plastic zone above the crack plane
R_1	residual radius of curvature measured for the wedge-peel test for the arm to which most of the adhesive remained attached after failure
R_2	residual radius of curvature measured for the wedge-peel test for the arm closer to the crack plane
R_a	average residual radius of curvature from the values R_1 and R_2
Γ_0	total energy dissipated in the cohesive zone in the CZM
Γ_b	total energy dissipated in the adhesive layer
Γ_p	total plastic energy dissipated in the adhesive layer
Γ_p^A	total plastic energy dissipated in zone A in the adhesive layer
Γ_p^B	total plastic energy dissipated in zone B in the adhesive layer
Γ_p^C	total plastic energy dissipated in zone C in the adhesive layer
η	non-dimensional parameter in the Swift hardening-law
κ	initial yield stress in the Swift hardening-law
ν	Poisson ratio
ν_s	Poisson ratio of the adherend material
σ_0	initial yield stress in the power-hardening law
σ_1	maximum principal stress
σ_c	critical maximum principal stress value used in the failure criterion
$\hat{\sigma}$	peak stress used in the CZM

between these two extremes. In their model, a single CZM is used which possesses zero height and has material parameters which define the shape and size of the CZM. The local fracture process is simulated by this cohesive zone and the local energy dissipation in the adhesive, ahead of the crack front, is accounted for by embedding the CZM between layers of elastic–plastic solid elements which represent the adhesive layer. A main feature of the model proposed by Martiny et al. [2,3] was that the values of these material parameters were held constant throughout the various modelling studies. The CZM was implemented in a two-dimensional (2D) plane-strain, large-rotation, quasi-static, steady-state, finite-element formulation.

In Martiny et al. [2], the authors showed that the CZM was capable of predicting accurately the failure of adhesive joints consisting of aluminium-alloy adherends bonded together with an epoxy-based adhesive, 'Bondmaster ESP 110', with an adhesive fracture energy, G_a, of the order of 1000 J/m^2. The values of the parameters that characterised the CZM of the adhesive were identified by using an elastic–plastic fracture-mechanics (EPFM) wedge-peel test configuration, coupled with an inverse-analysis method that was based on knowing the residual radii of curvature of the two adherend arms and the crack length. To validate the proposed numerical model, it was used, together with the now-fixed CZM properties, to predict successfully the effect of various geometric features for other configurations of the elastic–plastic wedge-peel test, e.g. the effect of the thickness of the adhesive layer. The model was also successfully applied to fixed-arm peel tests, subjected to various peel angles. The numerical results from the proposed model were also post-processed to extract values of the adhesive fracture energy, G_a. For this particular adhesive, these values were found to be not significantly dependent upon the details of the peel test configuration, including the thickness, h_{adh}, of the adhesive layer over a relatively very narrow range of 0.25–0.4 mm. Also, the values of G_a were in very good agreement with those measured using a linear-elastic fracture-mechanics (LEFM) tapered double-cantilever beam (TDCB) test method. These observations were attributed to the fact that the main contribution to G_a arose from the intrinsic work of fracture, Γ_0, i.e. the energy dissipated locally ahead of the crack tip by