Predictive fracture model for the steady-state failure of adhesive joints using the « plastic wedge peel test »

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ABSTRACT: *An extensive numerical study of the « plastic wedge peel test » is performed in order to analyse the mode I steady state debonding of a sandwich structure made of two thin metallic plates bonded with an adhesive. A cohesive zone model characterised by the maximum separation stress and the work of adhesion represents the behaviour of the adhesive bond. A steady-state finite element code accounting for finite rotation has been developed. All relevant parameters of the test have been studied in a wide range in order to describe their relationship with the parameters of the cohesive zone. An original method for identifying the cohesive zone parameters is presented and tested on experimental data generated with different adhesives.*

INTRODUCTION

The development of adhesive bonding of metallic substrates in many industrial applications goes along with the need for robust and well understood testing techniques; in particular when debonding involves plastic deformation of the substrates. Moreover, this need is accompanied by the complementary need to develop models for the transfer of laboratory tests results to the design of real structures. This study attempts to contribute to these two aspects of the problem with detailed analysis and modelling of the *plastic wedge peel test method* using an *embedded process zone* for modelling the adhesive. This work follows previous investigations by Thouless and co-workers [1,2]. In this test, two bonded metal plates are separated by means of a wedge inserted along the interface (Figure 1). If the plates are thin enough and the yield stress small enough, plastic bending of the substrates occurs during the failure of the adhesive bond leading to permanently curved substrates of radius R_1 and R_2.

In this work the EPZ is implemented within a steady-state finite element model [3]. This code is much more efficient than standard implicit FEM but although limited to steady state deformation and fracture problems.

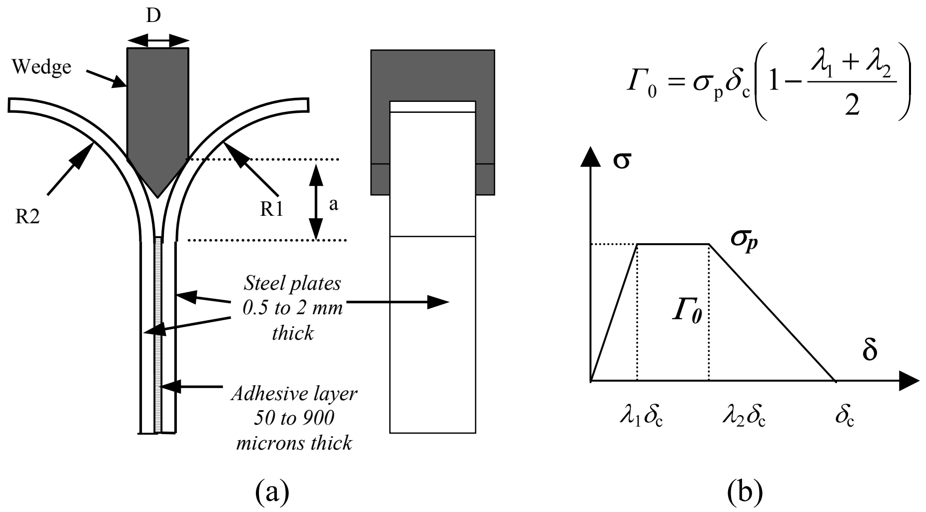

Figure 1: (a)The plastic wedge peel test ; (b) the traction separation law.

MODEL FOR STEADY STATE PLASTIC WEDGE TEST

The embedded process zone model

The adhesive layer is modelled as an interface traction-separation law which relates the normal stress σ to the normal displacements δ. The traction-separation law proposed by Tvergaard and Hutchinson [4] has the form depicted on Figure 1(b). The two relevant quantities characterising the EPZ are the area under the curve Γ_0, which represents the toughness of the joint, and the peak stress σ_p. Note that once the maximum separation δ_c, the peak stress σ_p, and the shape parameters λ_1 and λ_2 are fixed, Γ_0 can be directly obtained by the equation shown on Figure 1(b).

Since the EPZ models the entire adhesive layer, both the failure process and the deformation in the bulk of the adhesive are accounted for in an average sense by the traction separation law.

Parameters studied using the steady-state FEM code

The metallic substrate of thickness h is modelled using the isotropic elastic-plastic, rate independent J_2 flow theory with E as the Young's modulus, σ_0

the tensile yield stress and n the hardening exponent. The Poisson's ratio, ν, is always taken equal to 0.3 in this study. The behaviour of the adhesive layer is modelled as the traction – separation law characterised by Γ_0 and σ_p.

As the substrate plastically deforms, the radius of curvature, R, can be evaluated as well as the crack length which is the distance between the crack tip (i.e. the position where the crack opening is equal to δ_c) and the wedge (i.e. the location of the applied displacement boundary condition).

The system of Figure 1 (a) can be described by the following parameters: E, ν, σ_0, n (substrate); Γ_0, σ_p (adhesive layer); h (geometry of the test specimen) and D (height of the wedge). Dimensional analysis lead to normalise the radius of curvature R and crack length a by the substrate thickness h. They are functions of the following dimensionless parameters:

$$\frac{R}{h} = F_1\left\{\frac{\sigma_0}{E}, n, \nu, \frac{\Gamma_0}{\sigma_0 h}, \frac{\sigma_p}{\sigma_0}, \frac{D}{h}\right\} \quad ; \quad \frac{a}{h} = F_2\left\{\frac{\sigma_0}{E}, n, \nu, \frac{\Gamma_0}{\sigma_0 h}, \frac{\sigma_p}{\sigma_0}, \frac{D}{h}\right\}. \quad (1)$$

In the remainder of the paper, $\Gamma_0/\sigma_0 h$ will be referred to as the toughness, σ_p/σ_0 the peak stress, and D/h the wedge thickness.

Numerical procedure

A steady state finite element formulation for small strain-small rotation crack propagation problems was first applied by Dean and Hutchinson [3] and later implemented by other authors [5]. The formulation consists in finding an equilibrium solution for the displacements based on a previous approximate distribution of plastic strains and then integrating the plasticity laws along streamlines to determine new approximations for stresses and plastic strains. This procedure is repeated until convergence is achieved. A small strain, large rotation formulation is used.

Since the test is symmetrical, only half of the sandwich needs to be analysed. Plane strain conditions are assumed. The wedge is modelled with a fixed boundary condition at a normalised distance $D/2h$ from the plane of symmetry. Mesh convergence analysis has been carried out and results have also been compared with simulations obtained using the implicit FE code ABAQUS version 5.8.

By imposing different values of a/h and σ_p, all parameters involved in the test can be systematically investigated.

RESULTS OF THE NUMERICAL STEADY-STATE PLASTIC WEDGE TEST MODEL

The toughness of an adhesive joint can be evaluated from experimental data from wedge-opened plastic peel tests considering that the relationships between the cohesive zone properties and the parameters of the tests are known. The results describing the dependence of the normalised crack length and radius of curvature on the dimensionless parameters appearing in (1) will be presented in this section for realistic ranges of variations of the parameters, i.e. for typical metal/adhesive bonds.

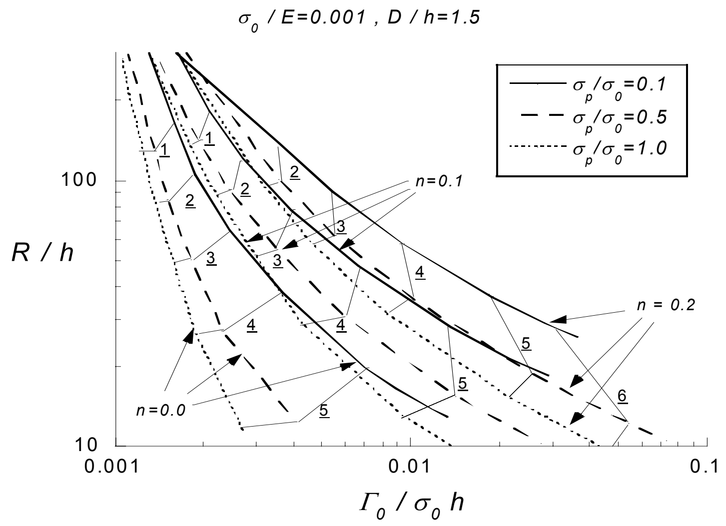

Figure 2: Variation of the radius of curvature and the crack length as a function of the toughness for σ_0/E=0.001; the iso-crack length curves are related to a number with 1 corresponding to a/h=15.9, 2 to a/h=11.9, 3 to a/h=9.9, 4 to a/h=7.85, 5 to a/h=5.8 and 6 to a/h=3.7.

Figures 2 shows the variation of the radius of curvature and crack length as a function of the normalised fracture toughness, for E/σ_0=0.001. Both R/h and a/h decrease with increasing toughness. An increase in toughness requires a larger bending moment in order to reach the critical state for cracking, leading to larger deformation in the substrate and to a smaller radius of curvature. For identical values of σ_p/σ_0 and $\Gamma_0/\sigma_0 h$, R/h increases with the hardening exponent n while a/h decreases with increasing n. Figures 3 shows similar results for σ_0/E equal to 0.003. In these Figures, the normalised wedge thickness *D/h* was always taken equal to 1.5. The effect of the variation of *D/h* is studied in Figure 3.

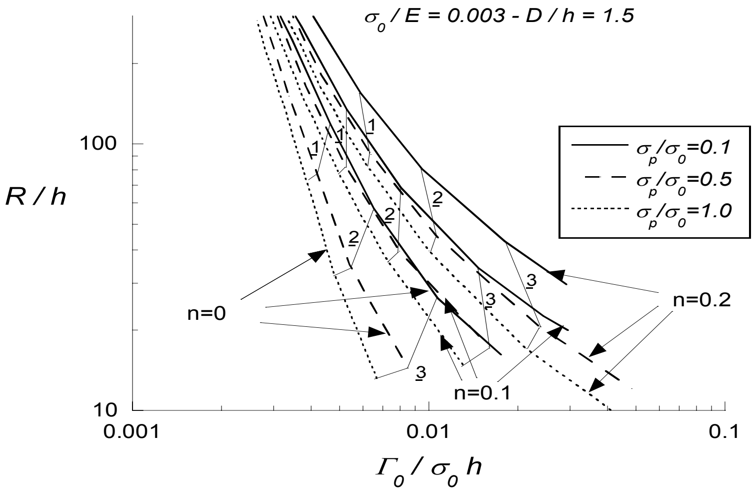

Figure 3: Variation of the radius of curvature and the crack length as a function of the toughness for σ_0/E=0.003; the iso-crack length curves are related to a number with 1 corresponding to a/h=7.85, 2 to a/h=5.8, and 3 to a/h=3.7.

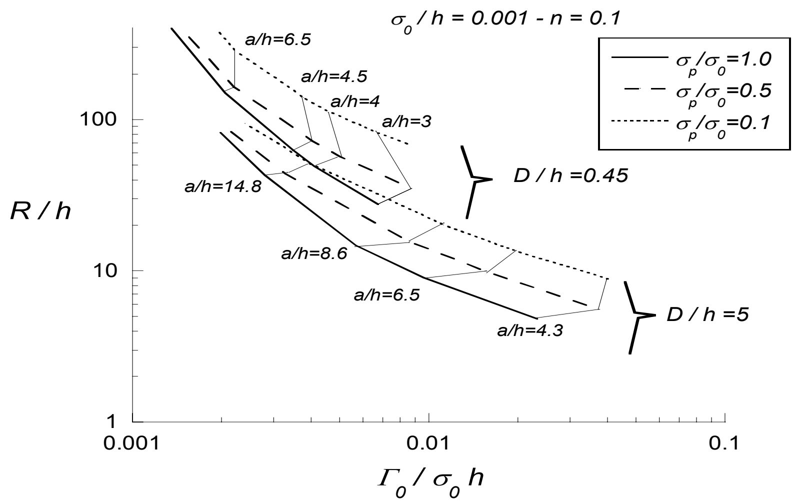

Figure 4: Variation of the radius of curvature and the crack length as a function of the toughness for two values of the wedge thickness with σ_0/E=0.01; the crack lengths are presented as iso-crack length curves.

DISCUSSION : CALIBRATION AND COMPARISON TO EXPERIMENTAL DATA

The functional dependence of the normalised radius R/h and the normalised crack length a/h on the normalised toughness $\Gamma_0/\sigma_0 h$ is highly non-linear. For a given value of the peak stress σ_p/σ_0, it can be seen that for any value of σ_0/E and D/h, an increase of the toughness goes along with a decrease of the radius of curvature of the substrate. For a given value of toughness, an increase of σ_0/E causes an increase of the corresponding value of R/h. This is due to the spring back effect which brings about an increase of the radius of curvature as a result of the decrease of the Young's modulus E. An increase of σ_0/E also amplifies the slope of these curves. In the same conditions and for a given toughness, a larger hardening exponent of the substrate leads to a decrease of the radius of curvature (and of the crack length) because substrates are more resistant to plastic bending. For a given toughness, a larger peak stress leads to a larger radius of curvature, in the range of peak stresses addressed in the calculation. At last, for a given adhesive and test specimen geometry, using a thicker wedge increases the crack length and diminishes the radius of curvature. Concerning the effect of the wedge thickness on the radius of curvature, this conclusion confirms results shown by Yang *et al* [2] which indicates that, if the wedge is too small, the deformation of the arms will be dominated by shear rather then by bending, leading to a smaller curvature.

Methods for identifying the EPZ parameters

As already mentioned, the plastic wedge test can be used for the evaluation of the adhesive toughness only if the bonded substrates deform plastically during debonding. The identification of the two parameters (Γ_0, σ_p) of the traction separation law requires at least two experimental independent measurement related to the plastic wedge test. These two experimental informations are of course the crack length and the average radius of curvature. Figure 5 illustrates the calibration method based on the measurement of the crack length and radius of curvature. First, we consider the iso-crack length curve corresponding to the experimental value of a/h. By drawing a horizontal line at the level of the measured average radius, the solution simply lies at the intersection of this line with the iso-crack length curve corresponding to the experimental value of this parameter. The peak stress has to be evaluated by interpolating between the "iso-σ_p" curves while the value of Γ_0 is directly obtained on the x-axis. In [6], another method based on two radii measured on two tests performed on specimens bonded using different substrate thickness is also presented.

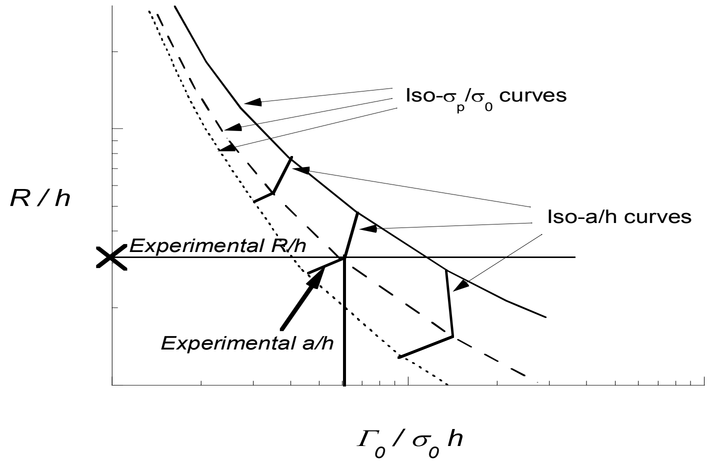

Figure 5: Calibration method of the cohesive zone model using the experimental radius of curvature and crack length.

Optimisation of the test

Some degree of freedom exists for choosing the material and thickness of the substrate allowing the most accurate calibration. Actually, all figures show that the radius of curvature and crack length are much more dependent on the peak stress for small radii of curvature. Figure 5 presenting the calibration method shows that the best situation is when the iso-crack length lines are as vertical as possible. Critical analysis of Figures 2 and 3 shows that the best choice for calibrating both the toughness and the peak stress is for high values of *n* and σ_0/E. Finally, Figure 5 shows that a small wedge thickness is slightly better for calibration although a thicker wedge gives rise to larger crack lengths, which are more easily measured.

Calibration of experimental results

Experimental data was obtained from plastic wedge tests performed on two adhesives layered in different thickness and joining steel substrates of 1.2 mm thick. Results translated in EPZ parameters using the calibration method presented in this paper are shown on Table 1. The value of the calibrated parameters for adhesive A are consistent with the one found by Yang *et al* [2] using another calibration method based on the evaluation of the stress in the adhesive layer. The variation of Γ_0 with bond thickness has two origins: first, the EPZ contains both deformation and fracture contributions. Second, the plastic constrain on the epoxy layer depends on the bond thickness; small thickness leads to a plastic zone that spreads out in the entire bond elevating the constraint thus decreasing the toughness as shown by Tvergaard and Hutchinson [7].

TABLE 1: Experimental data and calibration of EPZ parameters

	Bond thickness	*R/h*	*a/h*	Γ_0 *(kJ/m²)*	σ_p *(MPa)*
Adhesive A	0.05	24	4.8	*1.4*	*33*
	0.18	16	4.15	*2.7*	*83*
	0.90	17.5	4.2	*2.9*	*57*
Adhesive B	0.25	58	7.4	*0.86*	*16*

CONCLUSIONS

A systematical study has been made of all parameters involved in the plastic wedge peel test using finite element method. The adhesive was modelled using an embedded process zone (EPZ) characterised by an intrinsic toughness Γ_0 and a maximum stress σ_p. This study was made using a steady-state finite element code. Moreover, an original calibration method has been proposed for converting the experimental data into the EPZ properties. This calibration method was effectively used on experimental results obtained on different adhesive systems.

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