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PREDICTIVE FRACTURE MODEL FOR STEADY-STATE FAILURE OF ADHESIVELY-BONDED JOINTS WITH EXTENSIVE PLASTIC YIELDING

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ABSTRACT

This work deals with the development of predictive models for the failure of adhesively bonded joints. Experimentally, the focus lies on industrial thin steel plates bonded by modified epoxy adhesives. Experimentally, a « plastic wedge-opened double-cantilever beam test » is used to measure the mode I steady-state adhesion of a sandwich structure made of two thin steel plates bonded with an epoxy adhesive. The assemblies fail with extensive plastic deformation of the adherents. Two parameters are measured: the radius of curvature of the deformed steel adherents and the current crack length. Classical linear elastic fracture mechanics relationships are not accurate for addressing cracking with extensive plastic deformation. Numerical simulations are thus required to allow quantitative data reduction. A cohesive zone model has been chosen to represent the behaviour of the adhesive bond material. The cohesive zone is characterised by two parameters: the strength of the epoxy layer and its intrinsic fracture toughness. In this first part of the study, the entire adhesive layer is represented by one row of cohesive elements. A steady state FE code accounting for finite rotation has been developed. This formulation appears much more efficient and faster than the standard formulation although it is limited to steady-state processes. Calibration of the cohesive zone parameters has been performed through comparison with the experimental results.

KEYWORDS

Wedge-opening peel test, adhesive, bonding, toughness, cohesive zone model, steady state

INTRODUCTION

For the last ten years, adhesive bonding of metal plates has become a very popular method in several industrial sectors. Simultaneously, an urgent need for the characterization and prediction of the failure of bonded structures has emerged. Due to the wide range of possible constraints imposed by the metal substrates, depending on the geometry and loading configuration, the toughness of the joints has to be measured using a test adapted for the foreseen application. The demand for new robust testing techniques, in particular when debonding involves plastic deformation of the substrates, is accompanied by the necessity of developing models for the transfer of laboratory results to real structures. Ultimately, these models will allow a reduction of the number of tests required for covering the variety of possible structural applications.

Fracture toughness of bonded joints has been measured using a wedge-peel test popularized by Thouless *et al*. [1]. In this test, two bonded metal plates are separated by means of a wedge inserted along the interface (Figure 1). The wedge induces a constant separation on the plates. If the plates are of sufficiently low thickness and yield stress, plastic bending of the substrates occurs during the failure of the adhesive bond. Fracture toughness can be derived from the measured value of the remaining radii of curvature R_f of the plastically deformed metallic plates and of the crack length a during debonding. This last value is taken as the distance between the crack tip and the point of contact of the wedge with the steel plates.

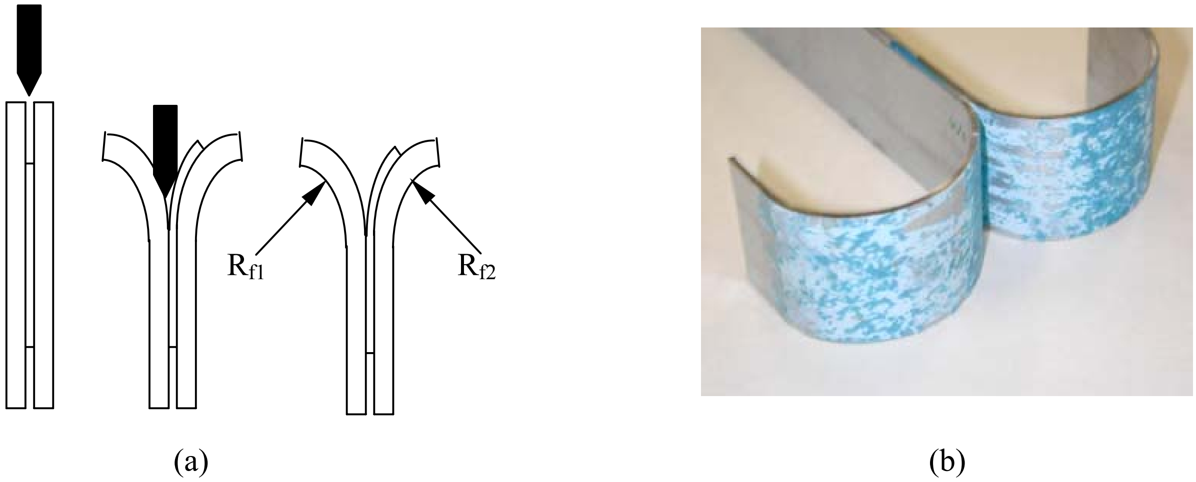

Figure 1: (a) Schematical presentation of the wedge-opening peel test, (b) Test specimen after fracture.

After a short transient following cracking initiation, the fracture process becomes steady state. The tests have been modeled using a steady-state finite element code. The deformation and fracture processes in the adhesive bond are represented by a traction-displacement or cohesive zone law, see [2,3,4]. The two key parameters of the cohesive zone model are the peak stress and the area under the traction-displacement curve, i.e. the work per unit area required for breaking the bond. A calibration procedure for these two parameters based on the wedge-peel test results is proposed and discussed.

EXPERIMENTAL PROCEDURE

Adhesively bonded joints were prepared using a commercial rubber modified epoxy-based adhesive for application in the automotive industry. This adhesive was deposited on steel plates between two Teflon tapes separated by 80 mm. The bond thickness was controlled by inserting uniform glass beads or metallic wires of diameter equal to the desired thickness of the adhesive layer between the plates. Specimen tests were made with different bond thickness. The adhesive between the plates was cured at 180°C for 45 minutes in order to obtain symmetrical specimens. The steel plates are produced by Cockerill Sambre Groupe Usinor. The plates are cut into coupons 200 mm long and 30 mm wide. Plate thicknesses of 0.78 mm and 1.16 mm were tested. The mechanical properties of the steel plates are given in Table 1.

The wedge-opening peel tests were performed using an Instron universal testing machine. A 1.8mm thick wedge was pushed down along the interface of the bonded joint of the specimen at a speed of 10 mm/min. After completion of the test, the radii of curvature of the two plastically deformed plates were measured using a profile projector. The bent substrates exhibited constant radii of curvature implying that the fracture operated in a steady-state manner. We also noticed failure to occur near one of the interfaces between the adhesive and the metal plate leading to a slightly asymmetrical mode of decohesion. The asymmetry sometimes induced significant differences between the two radii of curvature. Hence, an average of the two radii of curvature was used for subsequent data treatment.

TABLE 1

MECHANICAL PROPERTIES OF STEEL COUPONS FOR THE TWO DIFFERENT THICKNESSES

Thickness h (mm)	Yield stress σ_0 (Mpa)	Average hardening coefficient n
0.78	133	0.095
1.16	121	0.160

Figure 2 plots the variation of the average radius of curvature and crack length both normalized by the steel plate thickness (h=1.16 mm) as a function of the bond thickness. Each point on Figure 2 corresponds to the average of at least four different tests.

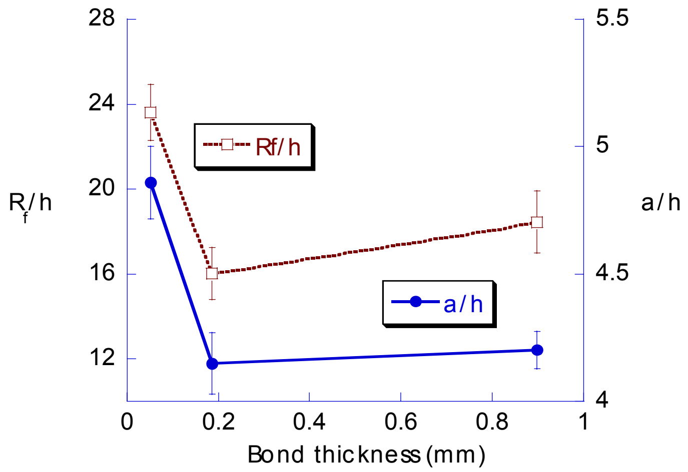

Figure 2: Average measured radii of curvature and crack lengths for the wedge-opening peel test with the adhesive bonded on a 1.16 mm thick steel plate which has n=0.16 and σ_0=121 MPa.

The reduction of the data consists of deriving the fracture toughness from the measured radius of curvature and crack length. Different methods have been investigated in other papers [5] relying on an analytical formula derived using beam theory and the energy release rate definition or based on the computational finite element model (FEM). Here, after a summary of analytical models, we propose a new method based on a steady-state finite element model.

ANALYTICAL BEAM MODEL

Considering steady state crack propagation, assuming that simple plastic beam theory applies, and that pure bending prevails, Yang *et al* [4] showed that:

$$\Gamma = \frac{Anh^{n+2}}{2^n (n+2)(n+1) R_f^{n+1}} \tag{1}$$

where n and A are material properties based on the Hollomon law, h is the metal beam thickness and R_f is the radius of curvature of the deformed beams.

This solution has aroused controversial discussion in Ref. [6,7,8]. Moreover, Sener [9] and Ferracin [5] have discussed the conditions when elastic-return of the metal adherent has a significant contribution to the toughness. Table 2 shows the toughnesses obtained with the complete model. The results presented in Table 2 show a decrease of the fracture toughness for thin adhesive layers due to the increasing confinement of the plastic zone. Quite surprisingly, the computed toughness decreases at very high adhesive thickness.

TABLE 2
CALCULATION OF TOUGHNESS USING AN ANALYTICAL EXPRESSION BASED ON PLASTIC BEAM THEORY

Joint thickness (mm)	Average radii of curvature (mm)	Toughness (kJ/m²)
0.050	27.38	0.87
0.185	18.57	1.33
0.898	21.39	1.07

COMPUTATIONAL STEADY-STATE FINITE ELEMENT MODEL

The fracture toughness can be estimated more accurately using a computational steady state FEM with a cohesive zone model (CZM) to simulate deformation and failure of the adhesive joint. The CZM consists of a traction-separation law whose general shape is given in Figure 3 as in Ref. [2,4]. The two relevant quantities characterizing the curve are the area under the curve Γ_0 which is the intrinsic toughness of the joint and the peak stress (which can be considered as the strength of the bond) σ_p. Notice that once the maximum separation δ_c, the peak stress σ_p and its shape parameters λ_1 and λ_2 are fixed, Γ_0 can be directly obtained from Eqn. 2.

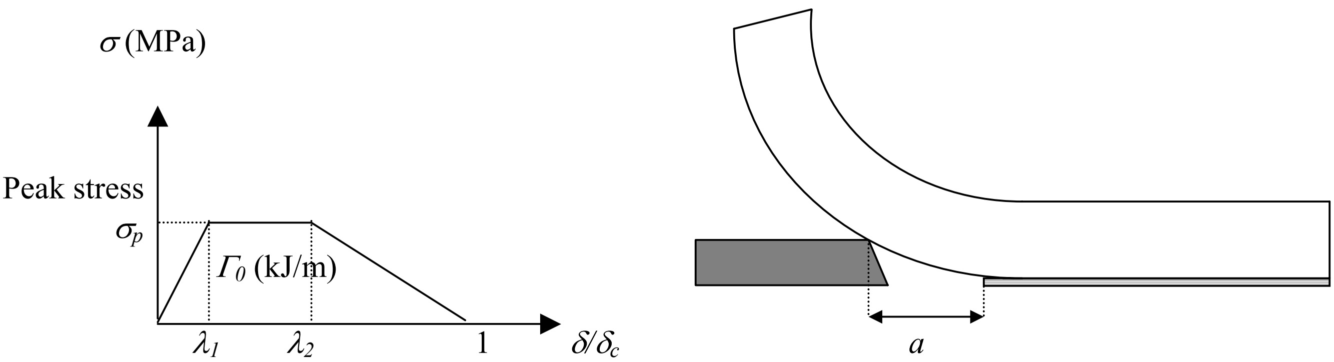

Figure 3: Traction separation law of the cohesive zone model and FEM model

$$\Gamma_0 = \frac{(1-\lambda_1-\lambda_2)}{2}\ \sigma_p\delta_c \qquad (2)$$

The steady state formulation was first applied by [10] and recently extended to rate dependent fracture of epoxy by Landis *et al*. in [11]. The formulation consists of 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.

Half of the specimen has been modeled using 8 node elements and the relevant boundary conditions have been imposed. Extensive mesh convergence analysis has been carried out. The mesh was particularly refined at the point of contact of the wedge and at the crack tip.

In a steady state formulation, most geometrical parameters like the crack length *a* can be fixed. The crack tip will effectively be located where it has been fixed if the crack tip opening displacement (CTOD) at this point is equal to the maximum separation of the cohezive zone δ_c. In order to determine the fracture parameters Γ_0 and σ_p the procedure was modified to update the value of σ_p by Eqn. 3 at each plasticity iteration so that when convergence is achieved, the value of the crack tip opening (CTO) equals δ_c.

$$\sigma_p = \sigma_p \frac{CTOD}{\delta_c} \tag{3}$$

The solution obtained by this method is then used as a guess value in a standard steady-state formulation. Results are in agreement using the modified formulation or the standard formulation with the value of σ_p taken from the results of the modified procedure. We have compared the steady-state results with the one obtained from the standard, non-steady state FEM code ABAQUS used with a cohesive zone implemented as a user's subroutine element. The results are almost identical, however the calculation time is far greater with ABAQUS.

The fracture process is described by the couple (Γ_0, σ_p) and thus the calibration of the model requires two different experimental measurements. These measurements are the average radius of curvature and the crack length.

The following strategy is used for the calibration of the parameters of the CZM with our experimental results:

1. Steady-state FE simulations of the wedge-opening peel test geometry are carried out imposing a particular experimental crack length and using different values of δ_c. Each of these simulations gives rise to one steady-state radius of curvature and to a particular value of σ_p. For each simulation, the value of Γ_0 is calculated from (2). These results can be represented in a plot similar to Figure 4.
2. From the experimental value of the radius of curvature R_f, one can easily match the Γ_0 and the σ_p as shown by the arrows of Figure 4.

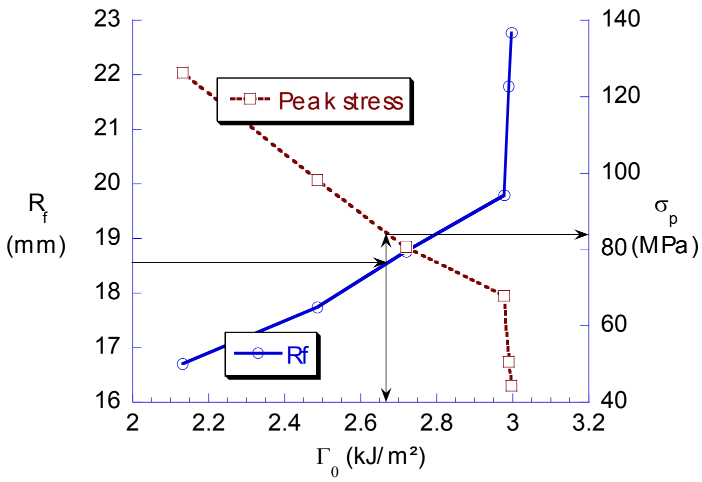

Figure 4: Calibration method used to calculate (Γ_0, σ_p) from (a, R_f).

Table 3 presents the calibration results obtained using this procedure. Although the peak stress in the adhesive layer has a maximum for an intermediate layer, the toughness of the joint keeps increasing with bond thickness. The value of the calibrated parameters are consistent with the one found by Yang *et al* [4] using another calibration method based on the evaluation of the stress in the adhesive layer.

TABLE 3
CALIBRATION RESULTS USING A STEADY-STATE FEM APPROACH

Joint thickness (mm)	Average radii of curvature (mm)	Crack length (mm)	Toughness (kJ/m²)	Peak stress (MPa)
0.050	27.38	5.638	1.43	32.9
0.185	18.57	4.813	2.69	83.2
0.898	21.39	4.874	2.88	56.6

The values calculated for a 0.185mm bond thickness were used to model the wedge-opening peel test with bonded assemblies made of 0.78mm thick steel plates. The results in terms of radii of curvature were predicted with an error less than 5%.

DISCUSSION AND CONCLUSION

The analytical beam model yields a toughness between 0.87 and 1.33 kJ/m² for the different bond thicknesses fractured at a wedge speed equal to 10 mm/min. These values are about a factor of 2 smaller than the ones obtained using the more accurate numerical approach. The analytical form is based on the assumption of pure bending, neglecting the contribution due to the opening force of the wedge, the contribution of shear forces and the deformation in the adhesive ahead of the crack tip. The FEM approach also showed a continuous increase of toughness with bond thickness.

In this paper, we have demonstrated how a computational FEM model with a cohesive zone law can be calibrated using two experimental measurements. This model offers a means to accurately evaluate the toughness of the joint and to assess the analytical formula. When properly calibrated the cohesive zone model can also be used in a standard FEM code for assessing the integrity of real structures. The robustness of the model has to be assessed with other experimental results with different plate thicknesses and plate properties. In principle, the model parameters have to be modified when the bond thickness is modified. Accounting for the bond thickness in a more fundamental way will require enriching the model such that the contribution of the overall deformation inside the bond and of the failure process are decoupled. This can be done by explicitly modeling the bulk adhesive. Furthermore, addressing the loading rate effect will require the introduction of some dependence of the peak stress on the opening rate in order to mimic the strain rate sensitivity of the polymeric bond (see [11]).

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