CONSTRAINT EFFECTS IN STEADY-STATE FRACTURE OF ADHESIVELY-BONDED JOINTS

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Abstract

This work deals with the development of a predictive model for the mode I failure of adhesively bonded joints based on plastic wedge-opened double-cantilever beam tests. The emphasis is placed on the effect of the bond line thickness on the joint toughness which is directly connected to the plastic dissipation in the adhesive layer. The model considers a finite thickness adhesive layer made of a plastically deforming material embedding a single row of cohesive zone elements representing the fracture process within the adhesive. Crack propagation is simulated using a steady-state finite element formulation. The parameters of the model are evaluated from experiments on two different adhesives representative of the behaviour expected for a wide range of adhesive systems. The model is shown to capture the effect of the bond line thickness as long as the fracture mechanisms are not affected by the geometry.

Introduction

The development of predictive models which overcome the limitations of the one-parameter fracture mechanics approach are necessary in order to properly address constraint effects in adhesively bonded joints. Constraint effects are related to the thickness and geometry of the adhesive and of the adherent or to the details of the loading configuration. Transferability of laboratory results to real structural components most often involves constraint effects. A first step in that direction has been undertaken by M. Thouless and co-workers [1,2], see also [3]. Their idea was to represent the bond line by a cohesive zone layer. A minimal cohesive zone model involves two parameters : the strength of the layer and the work of separation. This approach allows for instance relating measurements obtained using different type of testing methods (e.g. peel test and wedge opening test). It can also be extended to mixed mode loadings [4]. However, the model is too simple to encompass constraint effects associated to the details of the stress and strain distribution within the adhesive layer and which are directly connected to the geometry of the adhesive layer, the loading configuration and the geometry of the adherents.

This study focuses on the analysis of the mode 1 plastic wedge-opened double-cantilever beam test. The model presented in Fig. 1 considers a finite thickness adhesive layer made of an elastoplastic material embedding a single row of cohesive zone elements representing the fracture process. The adherents are also elastic-plastic with hardening. The bond toughness Γ is equal to $\Gamma_0 + \Gamma_p$, where Γ_0 is the work of fracture and Γ_p is the extra contribution to the bond toughness coming from the plastic dissipation within the adhesive layer. In this study, Γ_0 is taken as a material constant independent of the local stress state. Changing the adhesive or adherent thickness induces constraint effects by affecting the amount and intensity of the plastic deformation in the bond line, i.e. affecting Γ_p.

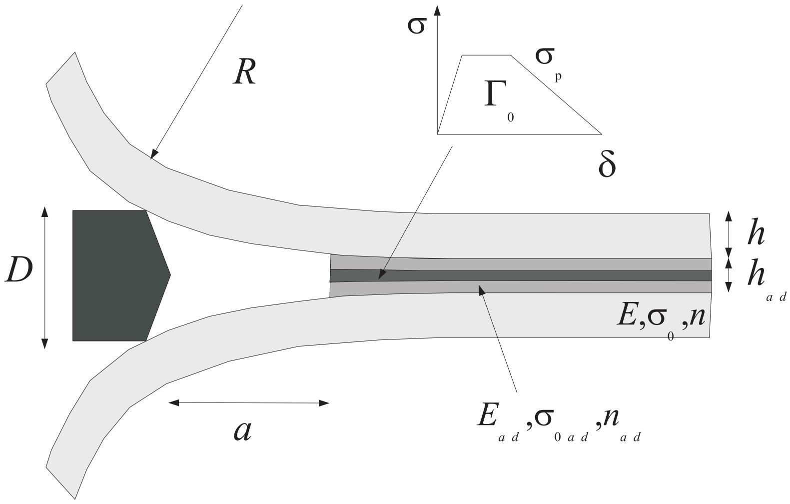


FIGURE 1. Model for the plastic wedge-opened double-cantilever beam test.

The aims of the paper are

- to validate the model from a comparison to experimental results obtained for two different adhesives tested with different bond line thickness, and
- to provide a better understanding of the constraint effects related to the adhesive thickness.

The experiments are described in a first section. The model is presented in the second section while the comparison/validation with the experiments and the discussion is proposed in the third section.

Materials and experiments

Adhesively bonded joints were prepared using two different commercial epoxy-based adhesives: (i) the first, called “yellow”, is a mono-component epoxy filled with a large amount of silicate particles to increase the stiffness; (ii) the second, called “blue”, is a mono-component epoxy formulated with 70% of epoxy resin diglycidyl ether of bisphenol-A incorporating 15% of a rubbery particles and 5% of very small silicate particles. The yellow adhesive shows a brittle behaviour under uniaxial tension with a Young’s modulus $E \approx 5$ GPa and a yield strength $\sigma_0 \approx 30$ MPa. The strain rate sensitivity is very weak. The blue adhesive shows a ductile behaviour under uniaxial tension with a Young’s modulus $E \approx 2$ GPa and a yield strength $\sigma_0 \approx 35$ MPa at intermediate strain rates. The strain rate sensitivity is moderate: $m \approx 0.05$ for the blue adhesive. (Note that strain rate effects will not be addressed in this paper.) The adhesives were 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. Samples with different bond thicknesses were produced.

The steel plates of thicknesses 0.78 mm and 1.2 mm were tested in uniaxial tension and the stress strain curves were fitted using :

$$\sigma = \begin{cases} E\varepsilon & (\sigma \le \sigma_0) \\ \dfrac{\sigma_0}{(\sigma_0 / E)^n}\varepsilon^n & (\sigma > \sigma_0) \end{cases} \quad (1)$$

where σ_0 = 150 MPa for both thicknesses and n = 0.19 and 0.16 for the 0.78 and 1.2 mm thicknesses, respectively.

Wedge-opening peel tests were performed on an universal testing machine at a speed of 10 mm/min using a 1.8mm thick wedge (see Fig. 2). The crack length was evaluated during the test using a traveling microscope. After completion of the test, the radii of curvature of the two plastically deformed plates were measured using a profile projector.

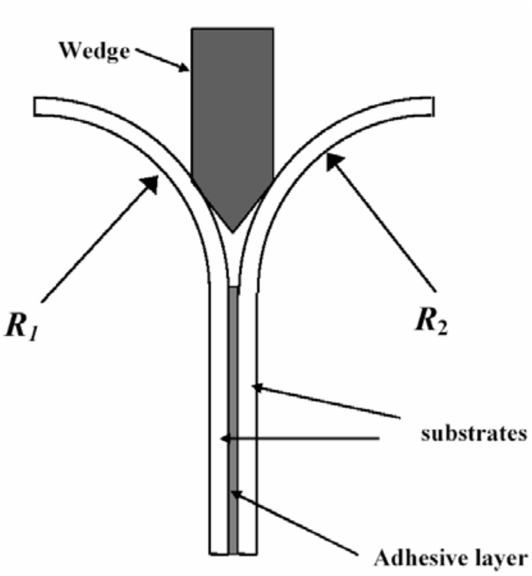


FIGURE 2. The plastic wedge-opened double-cantilever beam test. The fracture toughness is evaluated from the measurement of the radius of curvature of the permanently deformed arms.

Multiscale model for the wedge opening test

Both the adherents and the adhesives were modeled using isotropic linear elasticity (with Young's moduli E and E_{ad} and Poisson ratii ν and ν_{ad}) and the isotropic J_2 flow theory. The uniaxial response of the adhesive layer is also described using relation (1) involving a yield stress σ_{0ad} and a hardening exponent n_{ad}. Following earlier efforts by Tvergaard and Hutchinson [5], the fracture process within the adhesive layer is simulated using a cohesive zone model (see Fig. 1) characterized by the adhesive fracture energy noted Γ_0 and a peak stress noted σ_p. The three lengths entering the model are the wedge thickness D, the adherent thickness h and the bond line thickness h_{ad}. The outputs of the model that will be compared to experiments are: the radius of curvature of the arms R and the crack length a. Dimensional analysis shows that

$$\frac{R}{h} = F_1\left\{\underbrace{\frac{\sigma_0}{E}, n, \nu, \frac{\sigma_{0ad}}{E_{ad}}, n_{ad}, \nu_{ad}, \frac{\sigma_0}{\sigma_{0ad}}}_{\substack{elasto-plastic\ properties\\ of\ adherent\ and\ adhesive}}, \underbrace{\frac{\Gamma_0}{\sigma_{0ad} h_{ad}}, \frac{\sigma_p}{\sigma_{0ad}}}_{\substack{fracture\ properties\\ of\ adhesive}}, \underbrace{\frac{D}{h}, \frac{h}{h_{ad}}}_{geometry}\right\}$$
$$\frac{a}{h} = F_2\left\{\frac{\sigma_0}{E}, n, \nu, \frac{\sigma_{0ad}}{E_{ad}}, n_{ad}, \nu_{ad}, \frac{\sigma_0}{\sigma_{0ad}}, \frac{\Gamma_0}{\sigma_{0ad} h_{ad}}, \frac{\sigma_p}{\sigma_{0ad}}, \frac{D}{h}, \frac{h}{h_{ad}}\right\} \quad (2)$$

Another important outcome of the model is the plastic dissipation Γ_p in the bond line which is evaluated by integrating along the bond line thickness the plastic strain energy density far downstream. Finally the size of the plastic zone within the adhesive layer is also extracted from the simulations.

A finite rotation/small strain steady state finite element formulation is used to simulate the test (see [3] for details). Only half of the specimen is analysed. Plane strain conditions are assumed. A detailed mesh refinement analysis has been performed in order to ensure the convergence of the results.

Results and Discussion

Experimental results. The radii of curvature of the two adherents are never equal and a proper averaging is calculated [6]. Table 1 reports the value of the average radius of curvature R and crack length a for both adhesives for different bond thicknesses. The effect of the adhesive thickness is more marked for the yellow joints.

TABLE 1 – Experimental radius of curvature and crack length for the two adhesives and various bond thickness

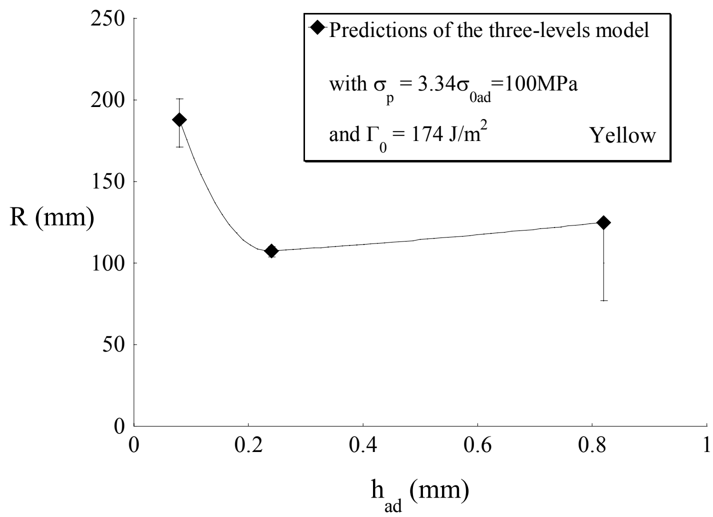
Adhesive	Substrate thickness (mm)	Bond thickness (mm)	R (mm)	a (mm)
Blue	1.2	0.05	27.4 ± 1.5	5.62 ± 0.2
Blue	1.2	0.18	18.4 ± 0.3	4.82 ± 0.15
Blue	1.2	0.89	21.5 ± 2.0	4.88 ± 0.1
Yellow	0.78	0.08	185 ± 15	11.3 ± 0.8
Yellow	0.78	0.24	109 ± 4	10.4 ± 0.3
Yellow	0.78	0.82	99 ± 23	10.8 ± 0.4

Identification of the parameters. The properties of the adhesives and adherents were given above. The hardening exponent of both the yellow and blue adhesives was arbitrarily chosen equal to 0.1. The peak stress σ_p and fracture energy Γ_0 were identified based on the values of R at two different specimen thicknesses. This procedure was preferred over an identification based on both the crack length and radius of curvature from a single specimen, as the measurement of the crack length is much less accurate. For the yellow adhesive, $\sigma_p = 3.34\sigma_{padhesive}$ = 100 MPa and Γ_0 = 174 J/m^2 while for the blue adhesive $\sigma_p = 3.25\sigma_{padhesive}$ = 114 MPa and Γ_0 = 3490 J/m^2 (which closely agrees with the fracture toughness measured on bulk CT samples $\mathcal{G}_{Ic}$ = 3200 J/m^2, see [6]).

Validation of the model. The predicted radii of curvature and crack lengths are compared to the experimental measurements in Figs. 3(a-d). The predictive potential of the model is assessed by:

(1) Finding a single set of fracture parameters Γ_0 and σ_p that allows reproducing the experimental evolution of R with the adhesive thickness, especially at the thickness not used in the identification process. The agreement for the yellow adhesive is excellent. In the case of the blue adhesive, it was not found possible to capture the marked decrease of the overall bond toughness (i.e. increase of R) at the smallest thickness with a single set of Γ_0 and σ_p. The explanation is twofold. First, fracture surface observations revealed that the length scale of the fracture mechanisms is on the order of a 100 μm in the thicker bond line. In the thin bond line, the fracture mechanisms are thus constrained by the thickness of the adhesive layer and cannot fully develop. The corresponding Γ_0 should thus certainly be lower than 3490 J/m^2. Introducing such type of length scale effect on the fracture mechanisms into the model requires much more advanced micromechanical approaches. It is also important to point out that fracture occurs in the middle of the bond line for the thin adhesive layer system and near the interface for thicker bond line. The location of the crack in the joint probably affects the plastic strain distribution and magnitude, hence the Γ_p contribution. This point has not been investigated yet.

(2) By producing values of σ_p that are physically acceptable. Peak stresses larger than 3 times the adhesive yield strength are indeed realistic (values larger than 3 are required to generate significant plasticity in the joint, see also [5]).



(a)

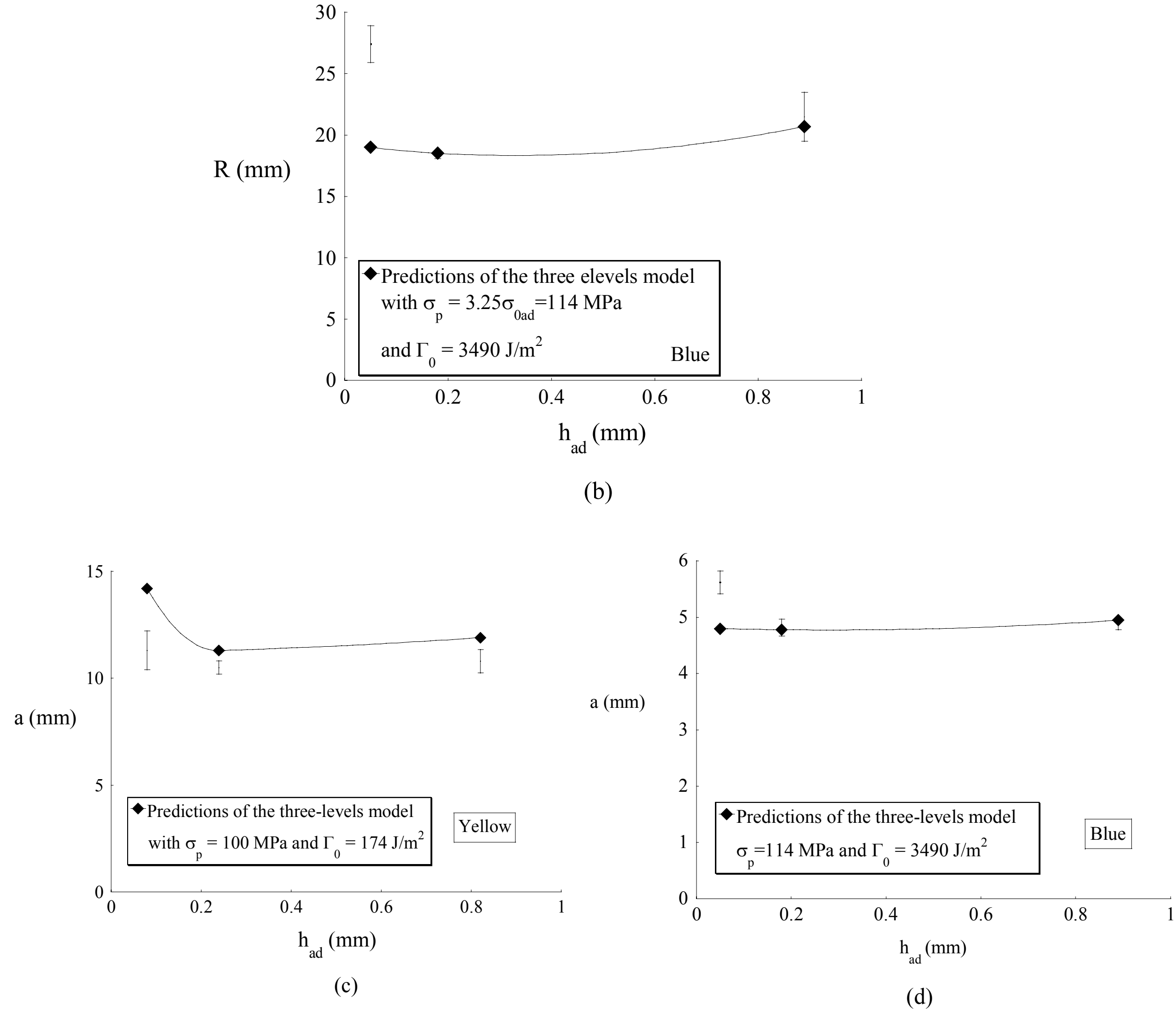


FIGURE 3. Comparison of the measured and predicted radius of curvature and crack lengths for blue and yellow adhesives

(3) By getting values for the crack length that agree with experiments, keeping in mind the experimental error on this parameter. In the yellow adhesive, the predictions are slightly too low (note that the experimental *a* constitute a lower bound). For the blue adhesive, the trends are similar to the trends obtained for the radius of curvature.

Probably the main limitations of the model comes from the use of the J_2 flow theory to represent the adhesive behaviour and from assuming a constant Γ_0 independent of the stress state and of the length scale imposed by the adhesive thickness.

Effect of the bond line thickness. Fig. 4 shows the variation of Γ/Γ_0 as a function of the different bond thickness for the two adhesives using the properties identified above. Simulations have been runned for a large range of adhesive thickness, well outside the range tested experimentally. Fig. 5 show the corresponding variation of the plastic zone height with the half bond line thickness. The variation of Γ/Γ_0 with the bond thickness observed in Fig. 4 and the accompanying evolution of the plastic zone height raises several comments:

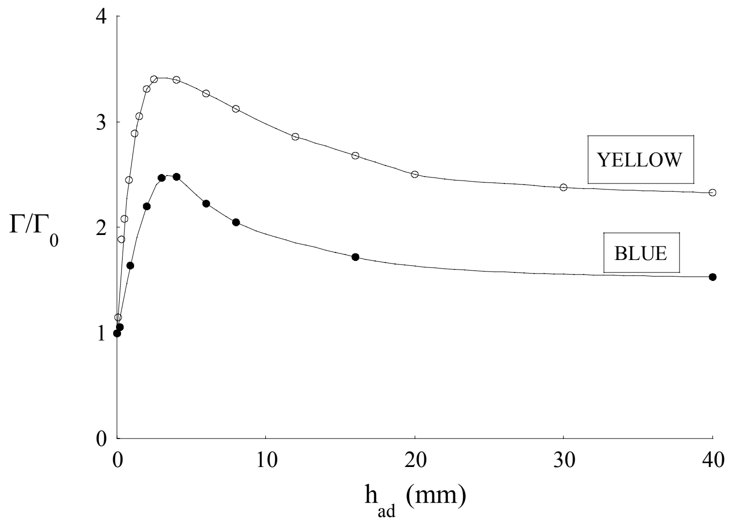


FIGURE 4. Variation of the ratio Γ/Γ_0 as a function of the bond line thickness.

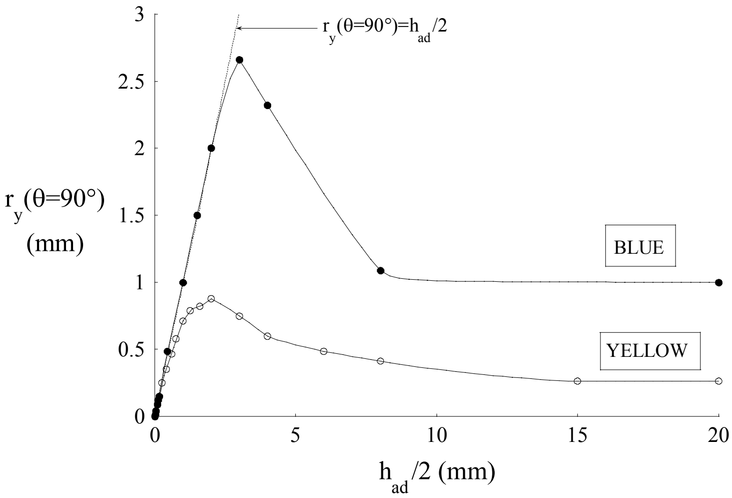


FIGURE 5. Variation of the height of the plastic zone as a function of half the bond line thickness for the two adhesives.

- For thin adhesive layers, the global toughness increases linearly with the bond line thickness. Realistic bond line thickness of most adhesive systems available commercially will fall into that category. As long as the bond thickness is small enough, the adhesive layer is fully plastic (the plastic zone height is thus exactly equal to the bond line thickness, see Fig. 5) and the state of plastic deformation is relatively homogenous, independent on the thickness of the bond. The work of plasticity per unit volume is thus constant and the work per unit area Γ_p is thus proportional to the bond line thickness. This result offers a means to evaluate experimentally Γ_0 by performing tests with different adhesive thicknesses (but thin enough !). Γ_0 is indeed a more intrinsic characteristic of the fracture resistance of the adhesive than Γ.

- For larger adhesive thicknesses, the ratio Γ/Γ_0 keeps increasing with the bond line thickness but in a non linear way. This non linear evolution corresponds to the fact that plastics strains become less and less homogenous. The joint is not fully plastic anymore. The plastic zone is surrounded by an elastic region. It becomes a large scale yielding problem which is much more complex to analyse than fully plastic (for which simple dimensional or energy arguments are usually very useful) and small scale yielding (for which one-parameter fracture mechanics solutions exist).

- When the bond line becomes sufficiently thick, the ratio Γ/Γ_0 attains a maximum which corresponds to the maximum plastic zone height and then it decreases to reach the small scale yielding (SSY) limit where the plastic zone is much smaller than the adhesive thickness. The plastic zone size under plane strain SSY conditions is equal to

$$r_y(\theta) = \alpha(\theta)\frac{1}{3\pi}\frac{E}{1-\nu^2}\frac{\Gamma_0}{\sigma_0^2} \quad (3)$$

  where θ is the angle made with respect to the crack plane. For $\theta = 90°$ (i.e. in order to evaluate the plastic zone height), the plastic zone size is usually significantly larger than for $\theta = 0°$. Typically $\alpha(90°)$ ranges between 1.25 to 5 depending on the T stress and Poisson ratio (see [7] p. 292). For the properties of the yellow adhesive the SSY plastic zone height predicted by (3) would be equal to about 120μm for $\alpha = 1$, while for the blue adhesive, it would be equal to 680 μm, values which agree with the predictions of Fig. 5 considering that α is larger than 1.

- Although, the plasticity is more extensive in the blue adhesive, the increase of toughness with adhesive thickness is less marked in the blue adhesive than in the yellow adhesive simply because the work of fracture Γ_0 is much larger in the blue adhesive.

To conclude, it is interesting to mention the analogy between the variation of the toughness exhibited in Fig. 4 and the evolution of the fracture toughness with plate thickness in the ductile tearing of thin sheets, see [8]. The effect of the bond line thickness can be taken into account only if the extension and intensity of the plastic deformation in the adhesive is properly modelled. Further researches aim at characterizing the constraint effect resulting from the loading configuration and adherent thickness as well as looking at more adequate constitutive models for the plasticity and damage of the adhesive material.

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