Fracture of Adhesive Layers in Mode II

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Abstract. Measuring fracture properties of adhesives in Mode II is often problematic. Indeed, no method can today be regarded as established by the community. In this paper a number of methods are presented. Experiments show that the evaluated properties of the same adhesive sometime vary considerably with the choice of specimen. Even just modest variations in loading conditions using the same specimen can yield considerable variation in the evaluated properties. Sources for these deficiencies are identified.

It has long been understood that Mode II testing using the end-notched flexure specimen (ENF) is conditionally stable. That is, the length of the crack has to be large enough to achieve a stable experiment. This is also the case for other Mode II specimens. A condition for stability is derived leading to an easily evaluated equation. Moreover, careful studies of the crack tip area during Mode II experiments often reveal an expansion of the adhesive during the final phase of loading. That is, negative Mode I loading. Due to the stiffness of the adherends, this leads to a compressive transversal loading of the process zone. Experiments and simulations show that the evaluated fracture energy depends on this constraint. A more detailed analysis of Mode II loading considering large-scale process zones gives some insight into the problem. It is also clear that Mode II has to be more carefully defined than is necessary for Mode I. Due to the transversal expansion of the process zone associated with shear, we may choose to define Mode II as a state of pure shear deformation or a state of pure shear stress. In experiments, none of these states are easily achieved. Moreover, transversally loaded short specimens can result in a process zone extending under the loading point. The result is compression of the process zone and exaggerated evaluated fracture energy. This problem is especially important to consider when evaluating soft and tough adhesives. If better understood and modelled, these effects might also be used in design so that an adhesive joint is loaded in a more favourable way.

Introduction

Shear loading is often considered favourable for adhesive joints. The fracture energy is usually considerably larger than in Mode I. Thus, a joint loaded in modes II and III give a stronger structure. However, measurement of the fracture properties in Mode II and III are often problematic. Specimens might fracture prematurely by instability and consistently evaluated fracture energies might be hard to achieve. The present paper presents some of the reasons for these difficulties and suggests some remedies. To understand these difficulties, three levels of complexity for models of adhesive layers are identified: the point model associated with linear elastic fracture mechanics; the surface model associated with cohesive models; and more detailed models where some features of the complex microstructure of the adhesive are captured. Moreover, some properties of the simulation models are also critically dependent on the model of the adherends. We here focus on thin adherends. That is, the in-plane dimensions, length and width are orders of magnitude larger than the thickness of the adherends. The thickness is usually somewhat larger than the thickness of the adhesive layer. To be concrete and use engineering applications from the automotive industry, the in-plane dimensions are of centimetre to meter of dimensions, the thickness of the adherends is typically about one millimetre and the thickness of the adhesive layers some fractions of a millimetre. In the lab, we prefer stronger adherends to simplify the evaluation of the experimental results. Still the height of the adherends is much larger than the thickness of the adhesive layer. In the industry, these adherends are usually modelled using shell theory. The stiffness of the adhesive is typically several orders of magnitude smaller than the stiffness of the adherends and it can withstand substantial deformation before fracture in the constrained state of an adhesive layer.

In the present paper, we focus on models and the conclusions that can be drawn from analyses and experiments more fully described elsewhere. To introduce some notation, Fig. 1a defines deformation and stress variables. Shear deformation and shear stress are denoted v and τ, respectively; peel stress and peel deformation by w and σ.

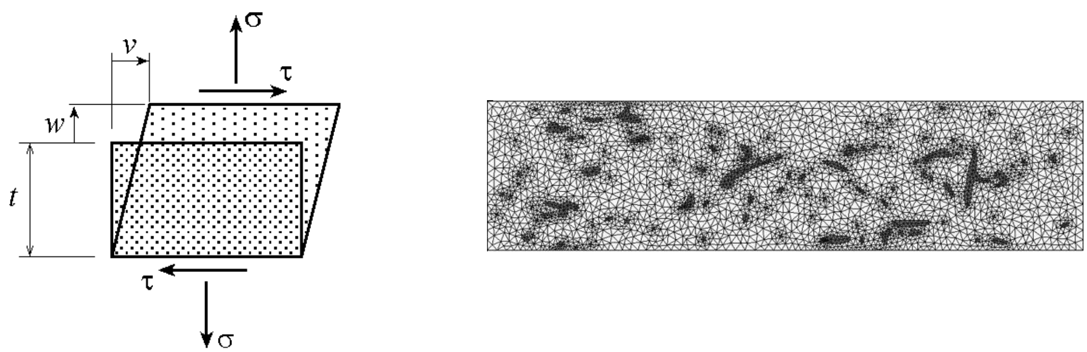

Fig. 1. a) Definition of loading of an adhesive layer; b) Detailed model of adhesive layer. Dark areas identified as mineral filling in the matrix of blended epoxy, [1].

Models

The adhesive. Engineering adhesives often consist of a basic polymer, e.g. epoxy and filling material toughening the adhesive and also reducing the cost. The polymer might be blended to achieve some multi functionality, e.g. an ability to take up remaining oil from the sheet pressing process. Examples of the most ambitious models of adhesives are given in [1, 2]. Fig. 1b illustrates a 2D-model of the epoxy adhesive DOW Betamate XW1044-3 with the layer thickness 0.2 mm. The matrix material is a blend of epoxy and a thermoplastic; the particles are identified as a mineral. The FE-model consists of conventional elements surrounded by cohesive elements. These facilitate the possibility of micro-cracks to initiate and grow into a macroscopic crack. The model is adjusted to experimental data using an optimization algorithm. This model is in the sequel referred to as the "detailed model". A cruder model is developed in [3] where the adhesive layer is modelled with regular elements and an "embedded process zone" is used to model crack growth, cf. Fig. 2a. This embedded process zone is a cohesive surface surrounded by a regular continuum. An even cruder model is achieved if a cohesive zone is used to model the complete adhesive layer [4,5], cf. Fig. 2b; this is the "cohesive zone model". A simplification of this model is the beam-adhesive layer model where the adhesive layer is considered to be linear elastic, for short the "B/A-model", [6]. This type of modelling has the longest history in strength analysis of adhesives, [7,8]. However in the industry, models where the adhesive is considered to be non-flexible is still considered state-of-the-art. This will be referred to as the "rigid adhesive model". The model can be identified as a linear elastic fracture mechanics model (LEFM) since its process zone is so minute that it is represented by a mathematical point. Two different models result depending on the model used for the adherends; if beam/shell models are used, no stress singularity is captured. The singularity is present if the adherends are modelled as 2D or 3D elastic continuum. Methods to evaluate the fracture energy from experimental results are typically based on the rigid adhesive model and beam theory, [9,10].

With an understanding of the limitations of the model, these methods rely on compensations for the flexibility of the layer, e.g. by adding some extra crack length to the equations.

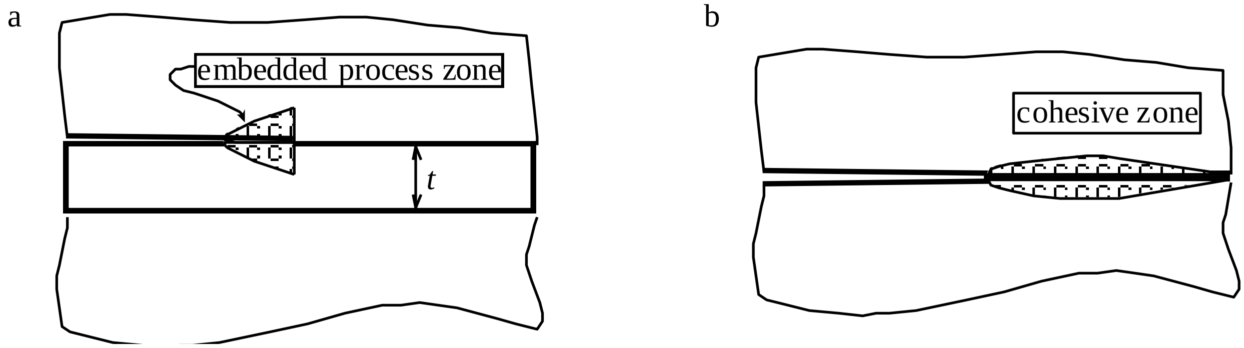

Fig. 2. a) Embedded process zone; b) Cohesive model

The adherends. Experimental methods are based on beam theory for the evaluation of the fracture properties of adhesives; in large-scale simulations of thin-walled structures, the 3D-version, shell theory, is used to model the adherends. This type of models is here denoted “beam theory”. More refined models are based on the full 2D- or 3D-fields of elasticity or elastoplasticity. In practice, these fields are most often analysed using the FE-method though an influential exception is given in [11]. This type of model is referred to as “full field models”.

A number of different combinations of these models of the adhesive and the adherends are studied and used in [12].

Fracture in Mode II

In industry, the shear lap joint is frequently referred to as a shear test of the adhesive. As obvious from the results in [8] and a large number of more recent studies, this load case is not one of pure shear. Due to the inevitable deformation of the specimen, the adhesive suffers a considerable peel loading. With a better understanding of stress analysis, the end-notched flexure (ENF) specimen is often preferred, cf. Fig. 3. From an experimental point of view, the specimen has its merits in a relatively simple loading state; a modest test rig is needed and the specimen is flexible which does not put too high demands on the stiffness of the test rig to achieve a state close to one of prescribed displacement. With linear elastic adherends, using the rigid adhesive model, and beam theory, the energy release rate in Mode II, J_{II}, is given by

$$J_{\mathrm{II}} = \frac{9M_{\mathrm{a}}^{2}}{Eb^{2}h^{3}}. \tag{1}$$

Where E, B, and H denote Young’s modulus of the material of the adherends, the out-of-plane width, and the height of the legs, respectively. The bending moment in the legs at the crack tip is denotes M_{a}. Equilibrium gives $M_{\mathrm{a}} = aPa/2$, where P, a, and α denote the load, the crack length, and the position of the load, respectively, cf. Fig. 3. It is noted in [13] that Eq. 1 holds for all transversally loaded specimens using this theory. Note that the identical upper and lower adherends need to be elastic.

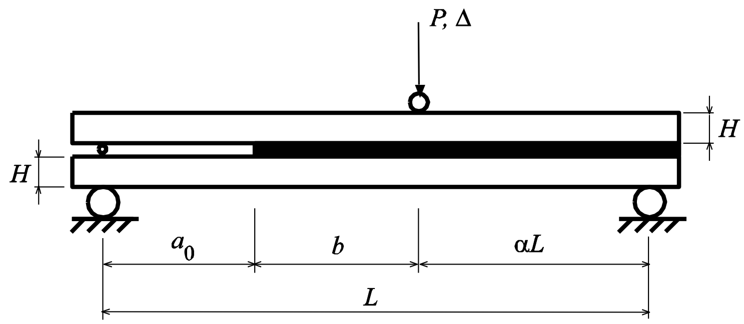

Fig. 3. End-notched flexure (ENF) specimen.

By considering the linear elasticity of the adhesive (the B/A-model), J_{II} increases to

$$J_{\text{II}} = \frac{9M_{\text{a}}^2}{EB^2H^3}\left(1+\frac{1}{ka}\right)^2, \tag{2}$$

where $k = 2\sqrt{(1+n)E_{\text{a}}/EHt}$ is a wave number associated with the stress state in the adhesive with Young's modulus E_{a}, Poisson's ratio ν, and thickness t, respectively, cf. [6]. Improving on this model by considering a cohesive model for the adhesive, we arrive at

$$J_{\text{II}} = \frac{9M_{\text{a}}^2}{EB^2H^3} + \frac{3aPv}{4EBH}, \tag{3}$$

where v is the shear deformation of the adhesive layer at the crack tip, [14,15]. In [16] it is shown that the second term can be substantial, i.e. ignoring the flexibility of the adhesive layer may be grossly misleading.

Fracture process. In [16], the fracture process of an engineering epoxy is studied. Fig. 4 shows a sequence of close up images of the originally 0.2 mm thick adhesive layer during an ENF-experiment. Although one can expect a compressive load at the crack tip due to the transmission of transversal loading from the upper to the lower legs of the specimen, the crack tip area expands in the transversal direction at the crack-tip area when the major crack is about to form, i.e. $w > 0$. In pure shear deformation, the volume of the material is preserved. However in the fracture process, micro cracks form. In order for these to be able to grow in volume, the adhesive layer has to expand; hence the peel deformation is necessary. This peel deformation is only necessary at the crack-tip area. Further away from this area, the adhesive is in a state closer to a state of pure shear deformation. That is, the adherends have to bend in order to open close to the crack-tip. This results in a substantial compressive peel loading at the crack-tip. The size and severity of this compression is to a large extent an open question. It is reasonable to assume that the compression depends on the bending stiffness of the adherends; with stiffer adherends, the compression can be assumed to be larger. Effects of this compression are obvious in studies with the detailed model in [17]. By constraining the peel deformation and loading a representative element of the adhesive with a prescribed shear deformation, the strength is considerably larger than in the case where the representative element is loaded in shear and letting it expand freely in the peel direction. These observations lead to questions regarding the definition of Mode II loading.

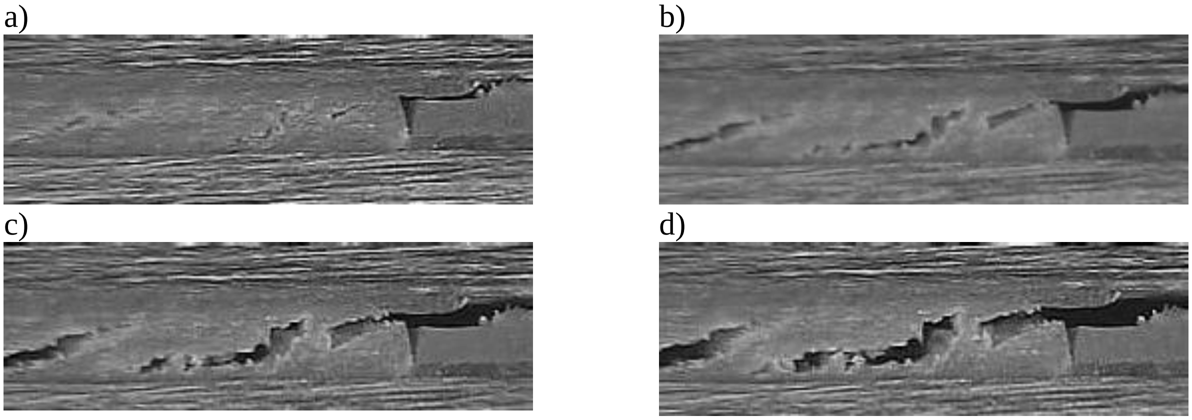

Fig. 4. Deformation process of the adhesive layer during ENF-experiment, [16]. Images (a), (b) (c) and (d) are in consecutive order. The Teflon insert at the right end in each image is 0.2 mm thick. The separation *w* in image (d) is substantial. The adhesive layer is observed at the free surface of the specimen. Due to a minute grading of the adherends, the layer appears thicker than the Teflon insert.

Definition of Mode II. With symmetric specimens, i.e. identical upper and lower beams, Mode II can be defined as a state where the beams deform identically and $w = 0$, cf. Fig. 1a. This definition is consistent with the conventional definition of Mode II in LEFM. However, this load case seems impossible to achieve experimentally by the reasons discussed above. The other alternative, also consistent with the definition of Mode II in LEFM, is to define it to be a state of pure shear stress. Note, that a state of pure shear necessitates shear traction also on the vertical boundaries in Fig. 1a. However, close to fracture, the shear stress is small and this might turn out to be a manageable deficiency of a useful definition of Mode II. Although the seriousness of this problem, we prefer this definition since it seems easier to achieve something similar experimentally than the alternative definition.

Stability. Shear loading typically results in problems with stability. Using the rigid adhesive model, beam theory and linear elasticity, stability is secured if the crack length is larger than a critical crack length a_{cr} given by

$$a_{\mathrm{cr}} = L\sqrt[3]{\frac{3c_0}{4\bar{J}}}\,. \qquad (4)$$

Here, $c_0 = Ebh^3C(0)/L^3$ and $\bar{J} = JEb^2h^3/(Pa)^2$ are non-dimensional compliances and energy release rates, respectively with $C(0)$ as the compliance of the specimen without a crack and J as the energy release rate; $\bar{J} = 9/16$ for the ENF-specimen with $\alpha = 1/2$, [13]. As shown in [13], Eq. 4 is valid for all transversally loaded specimens irrespective of loading case. It is also shown that an expansion to the B/A-model promotes stability, i.e. the critical crack length will be somewhat smaller considering the flexibility of the adhesive layer. A too short crack length leads to premature fracture. The result is a too small evaluated fracture energy, cf. [16].

Compressed process zone. With modern tough adhesives, the length of the process zone, i.e. the zone with inelastic response of the adhesive, is substantial. In [16] lengths larger than the height of the adherends are reported. However, cost efficient experimental methods are in demand and it is tempting to try to use small specimens. In [18] an alternative method is presented. The method allows for plastic deformation of the adherends. Using the path independent J-integral, the energy release rate is given by

$$J = \frac{P}{B}\left[\alpha\theta_1 - \theta_2 + (1-\alpha)\theta_3\right]. \qquad (5)$$

Here θ_i (i = 1,2,3) are the clockwise rotations of the support and loading points from left to right in Fig. 3. Fig. 5a shows the results from two alternative evaluations of J for the crash resistant adhesive Sika Power-498 at room temperature with layer thickness 0.3 mm, [19].

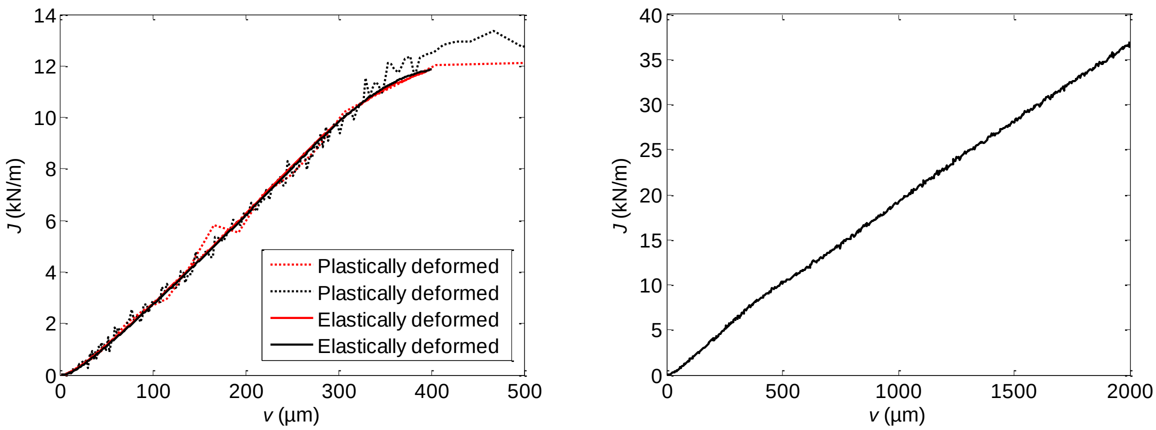

Fig. 5. *Left*: Evaluated energy release rate vs. shear deformation using two different specimen configurations Eq. 3 (elastically deformed ENF) and Eq. 5 (plastically deformed ENF) and 0.3 mm thick adhesive, [19]. *Right*: Evaluated energy release rate vs. shear deformation with 1 mm thick adhesive.

As shown, the fracture energy can be identified to about 13 kJ/m^2 irrespective of the method used. It should be stressed that the dimensions of the specimens are very different. With elastically deforming adherends, the length of the specimen, L = 1 m; with the plastically deforming adherends L = 0.2 m. However, when testing the same adhesive with the layer thickness 1 mm using plastically deforming adherends and Eq. 5, the results in the right part of Fig. 5 is achieved. That is, the energy release rate increases without bounds. Fig. 6 shows the corresponding load vs. load point displacement record. It is shown that no maximum load is achieved. However, as shown in the right part of Fig. 6, an interface has grown considerably during the experiment. Thus, a crack is formed without being noticeable in the evaluation. The important difference between the two test set-ups using plastically deforming adherends is the different thicknesses of the adhesive layer. With a 1 mm thick layer, the adhesive is considerably softer; the compliance scales linearly with the thickness of the layer. It is also considerably tougher; about twice the fracture energy is reported in [19] for this adhesive. The puzzling result is understood by considering that a large process zone is associated with the tougher and more flexible adhesive. The distance between the crack tip and the loading point, b = 30 mm (Fig. 3), is too small to capture this process zone. Moreover, the load is transmitted from the upper to the lower adherend by the adhesive layer. Thus, there is a compressive vertical stress in the adhesive under the loading point. This stress is more concentrated and larger with a more compliant adhesive layer. This compression is believed to hinder the expansion of the process zone and thus make the specimen stronger.

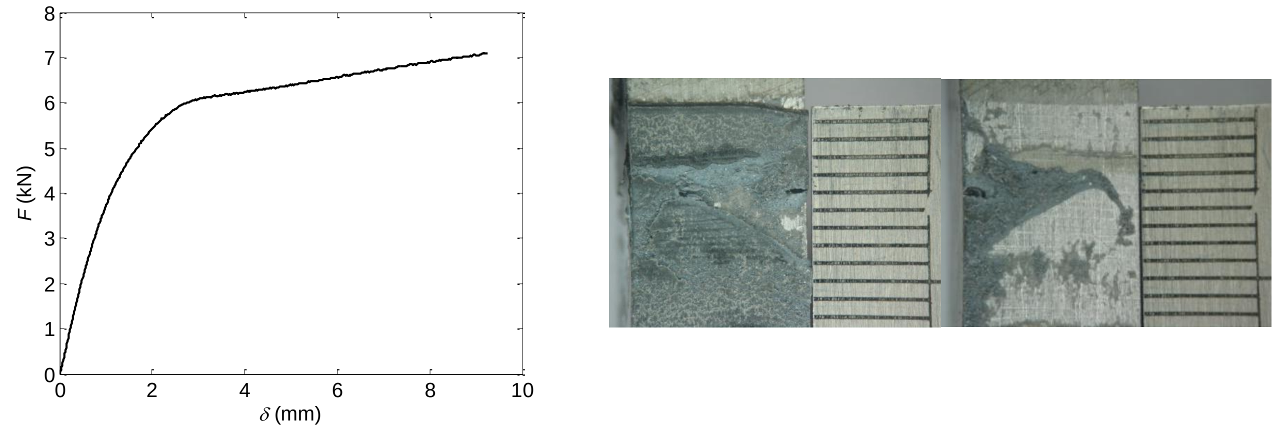

Fig. 6. *Left*: Load vs. load point displacement with 1 mm thick adhesive. *Right*: Corresponding fracture surface; upper and lower adherend showing adhesive fracture. Crack growing from top to bottom in the images; a ruler is inserted in the images with 1 mm marks.

Conclusions

Different models for adhesive systems show somewhat different results. Using beam/shell models for the adherends results in somewhat larger process zones due to the constraints imposed in these theories. However, the structural response, e.g. the fracture load, can be adequately captured, cf. e.g. [20]. The simplest model gives an easily evaluated criterion for stability; cf. Eq. 4 that is often adequate for the design of specimens. Using the ENF-specimen, two different evaluation methods give Eqs. 3 and 5 that gives almost identical results when testing a tough engineering adhesive. However, the distance between the crack tip and the loading point has to be large enough. It is shown that a too short distance may result in a compression of the process zone that results in a situation where no reasonable maximum load is achieved. Still some research has to be performed before all these aspects can be collected in easily accessible design rules and test procedures.

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