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Shear strength of adhesive layers – Models and experiments

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ABSTRACT

The mode II properties of adhesives joints are of special interest since these joints are strongest if loaded in shear. Today no standardized method is available to measure shear properties. After a brief discussion of different models used to analyse adhesive joints, we identify some of the reasons for problems that arise in some of the more frequently used experimental methods. It is shown that transversally loaded specimens with elastically deforming adherends can lead to unstable crack growth provided the un-cracked specimen is flexible. With tough adhesives, a substantial process zone develops at the crack tip. That is, most specimens are in a state of large scale yielding. If not properly taken into account, the evaluated properties will be in error. Moreover, the process zone may grow in under the loading point which hinders its evolution and yield errors in the evaluated properties. Modest variations in loading conditions using the same specimen can yield considerable variation in the evaluated properties. However, properly designed and used, both the thick-adherend lap-shear joint and the end-notched flexure specimen provide useful results.

1. Introduction

Shear loading is often considered favourable for adhesive joints. These joints are usually considerably weaker in mode I. Thus, joints loaded in modes II and III give stronger structures. With modern tough adhesives, the inelastic zone at the crack tip has a considerable extension at fracture. The fracture process is normally governed by nucleation, growth and subsequent coalescence of small cracks in the adhesive layer. In shear, these cracks initiate in local mode I. That is in 45° direction relative to the direction of shear loading. When a crack tip approaches the interface to the stiff adherend, the crack changes direction and grows parallel to the adherends. Subsequently they coalesce to form a macroscopic mode II crack, cf. [1]. This morphology of the fracture process is observed in many adhesives from soft and flexible polyurethane based adhesives (PUR) to stiff epoxies. Thus, it might be tempting to use the same or similar experimental methods to characterize all adhesives. As illustrated in the present paper, this is not a practical strategy. The size of the inelastic zone is usually many times larger than the thickness of the adhesive layer and it might even be larger than the height of the adherends, cf. [2]. This indicates that interactions of the process zone in the adhesive layer with the adherends are of importance for the fracture properties of an adhesive layer. This is also apparent from the influence of the thickness of the adhesive layer on the fracture energy, cf. e.g. [3]. Thus, the adherends constrain the fracture process zone in the adhesive layer in a way that needs to be considered in the evaluation of the fracture properties. However, the large difference in stiffness between metal adherends and polymeric adhesives indicates that the fracture properties should not be too sensitive to the properties of the adherends as long as

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Nomenclature

α	non-dimensional measure of the position of the loading point
Δ	displacement of loading point
θ	rotation at loading point
σ	peel stress
τ	shear stress
a	crack length
a_{cr}	critical crack length for stability
b	distance between crack tip and loading point for ENF-specimen
B	width of adherend
C	compliance
c_0	non-dimensional compliance
E	Young's modulus for the adherends
H	height of adherend
J_{II}	energy release rate in mode II
$\bar{J}$	non-dimensional energy release rate
L	length between outer support for test specimen
M_a	bending moment in adherend at crack tip
F	transversal load
t	thickness of adhesive layer
v	shear deformation
w	peel deformation

fracture occurs in the adhesive layer, i.e. cohesive fracture. On the other hand, if cracks grow in the interface between the adhesive and the adherends, the situation is complicated and we expect the fracture properties to depend on the interaction of the materials constituting the interface. That is, properties measured with one set of adherends cannot safely be used for another set of adherends. To achieve transferable properties of a joint, adhesive failure should be avoided. That is, the strength of the interfaces should be larger than the strength of the adhesive.

Measurements of the fracture properties in modes 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. These difficulties are elucidated with experimental results from studies of different adhesives. It is demonstrated that one method/specimen design that gives proper results for one adhesive gives erroneous results with other adhesives. To understand these difficulties, three levels of complexity for models of adhesive layers are identified: *the point model* associated with 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 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. To be concrete and use engineering applications from the automotive industry, the smallest in-plane dimension is some centimetre, 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 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. In the constrained state, the adhesive layer can withstand substantial deformation before fracture; typically up to 100% of engineering strain. This can be compared with the fracture strain of the same adhesive in a dog-bone experiment, i.e. in a state of uniaxial stress where fracture occurs at about 2–3% with the same adhesive, cf. [4].

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 for an adhesive layer with the thickness t. Shear deformation and shear stress are denoted v and τ, respectively; peel stress and peel deformation by w and σ. We here aim at identifying different sources for possible errors in the experimental evaluation of the shear properties of adhesives. Different specimen configurations are presented and their strengths and weaknesses are identified using adhesives ranging from soft and thick PUR adhesives to stiff and thin epoxies. This gives a good opportunity to demonstrate the possibilities and limitations with different methods.

2. Models

Experiments are always evaluated in relation to a theory. This section gives a brief description of typical materials and models. Different models for adhesive systems show somewhat different results. Using beam/shell models for the adherends results in a too large process zone due to the constraints imposed by these theories. That is, the limited ability of a beam/