Quantifying Design Properties of Adhesives

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Introduction

Virtual simulation of bonded components to predict deformation and failure under arbitrary loads is a holy grail of adhesive joint design. Advances in computational speed and developments in finite element (FE) modelling packages are improving simulation capabilities. However, a much greater understanding of how to model adhesives and obtain accurate engineering properties is required.

A series of research programmes on the Performance of Adhesive Joints has addressed the modelling, data and measurement method requirements needed for accurately characterising both structural and flexible adhesives. The approach has been to consider the adhesives as non-linear continuum materials whose loading response can be modelled using FE methods and failure criteria to assess the onset of adhesive rupture.

Quantitative techniques for modelling both the impact properties and durability performance of bonded structures have been developed [1-3]. Better understanding of test methods has led to advances in the accurate measurement of adhesive properties. This paper describes some of the results of this research that help engineers and designers to accurately quantify the material properties of adhesives and simulate the behaviour of structures. Complementing this work is a new project that aims to improve bond reliability through a better understanding of the surface characteristics controlling adhesion and environmental resistance. This is to be achieved through the development of quantitative relationships between key measurable surface properties and interfacial adhesion strengths.

Design Parameters

Model simulations require basic elastic property data, such as Young's modulus and Poisson's ratio, however to characterise the non-linear large strain response of flexible adhesives, parameters describing plasticity and flow [1, 2] or hyperelastic behaviour [3] are required.

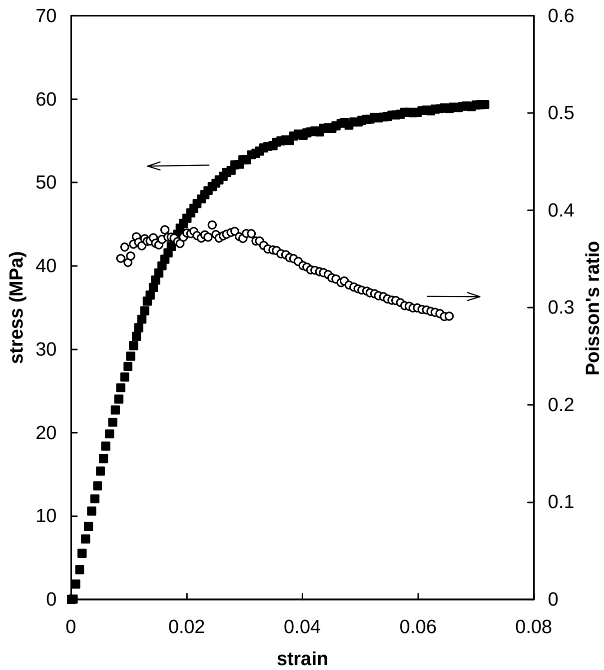

Figure 1: Tensile properties of a toughened structural adhesive.

Poisson's ratio assumes greater importance in the prediction of adhesive joint performance than is normally assumed [1]. The constraint against contraction imposed by rigid adherends can lead to large hydrostatic stresses in the adhesive, particularly near the interface where failure usually initiates. The determination of failure criteria requires accurate predictions of the stress and strain distribution in these regions. As Figure 1 shows, the value of Poisson's ratio for a structural adhesive can decrease as the adhesive yields. With flexible adhesives, the Poisson's ratio determined in uniaxial tension tests can be used to calculate the volumetric parameters for hyperelastic models [3].

Joint Tests for Engineering Properties

Design data are most accurately obtained through tests on bulk adhesive specimens under different states of stress. Standard methods for preparing such samples have been developed [4]. However, it may not always be possible to make bulk adhesive specimens of suitable quality. Only a limited number of adhesive joint tests, with rigid adherends to reduce cleavage and loaded to give uniform stress states, can provide accurate engineering properties.

Figure 2: An accurate alignment fixture improves the reliability of the butt-joint test data.

Shear properties can be obtained from the thick adherend shear test (TAST) or the butt joint torsion test [5]. Both of these methods, with suitable extensometry, can provide accurate values for the shear modulus. Failure in shear joints tends to initiate at tensile stress concentrations. In this respect, the essentially pure shear nature of the torsion test means that large strains can be achieved. Tensile stress concentrations at the corners of the TAST usually initiate failure, limiting the maximum extension. Stress concentrations can be reduced by rounding the corners of the adherends and by controlling fillet geometry, extending the range of the test.

To achieve a uniform state of stress and, thus, avoid cleavage forces in the butt tension test requires accurate alignment during specimen preparation and testing [1]. The normal alignment accuracy of tensile testing machines proved insufficient for obtaining reliable butt tension data as extension measurements made at points around the circumference of the bond line tended to diverge well before the maximum load was reached. Adequate alignment was obtained using additional fixtures that can adjust both the position and tilt of the connections between load frame and machine crossheads (Figure 2). Alignment software is used to guide adjustments to the fixtures until bending moments in a strain gauged 'dummy' specimen are eliminated. Once bending has been eliminated the fixture is locked and the joint specimen replaces the dummy specimen and is clamped rigidly into position.

The constraint imposed on the thin bond layer in the butt joint by the rigid adherends leads to a high component of hydrostatic stress when extended. This makes the butt tension test a good discriminator between plastic yield models proposed for toughened structural adhesives. However, the hydrostatic stress complicates the interpretation of elastic property data. If the stress distribution in the adhesive layer is assumed to be uniform then the slope of the stress-strain curve can be related to Young's modulus E and Poisson's ratio ν:

$$\frac{\sigma}{\varepsilon} = \frac{E(1-\upsilon)}{(1+\upsilon)(1-2\upsilon)} \qquad (1)$$

If the shear modulus G is known then the equation:

$$G = \frac{E}{2(1+\upsilon)} \qquad (2)$$

can be substituted into Eqn (1) to produce a quadratic function of either E or ν that can be solved to determine the elastic properties.

These properties are sufficient to predict the low strain, linear-elastic response of bonded structures. This is suitable for designing structures bonded with earlier generation brittle structural adhesives. However, characterisation of the non-linear large strain response of structures bonded with toughened adhesives requires inclusion of their plasticity behaviour. The basic strain hardening curves required for modelling using the simple von Mises yield criterion can be obtained, with care, from shear tests such as the thick adherend shear test. However, this criterion, which only considers shear yielding, does not accurately represent polymers where yield is also influenced by hydrostatic stresses.

Obtaining parameters that describe the hydrostatic stress sensitivity for models, such as the Drucker-Prager, requires test data from an additional state of stress. If bulk tension specimen manufacture is difficult then carrying out compression tests, requiring relatively small samples, may be an easier option. It must be possible to prepare a parallel faced, unbonded specimen, which requires low energy release surfaces. The compression test should take place between two flat, smooth, parallel platens. These should be lubricated to reduce friction to ensure a uniform stress state. The determination of strain from extensometers attached to the platens is prone to uncertainty, particularly at small deflections, but the main data determined from this test, yield stresses at larger strains, should not be significantly affected by the strain measurement.

The hydrostatic stress-sensitive models currently available do not accurately predict the multi-axial behaviour of modern rubber-toughened adhesives. Development of new materials models, incorporating the effects of rubber cavitation, is ongoing [1, 4]. This research should improve the accuracy of stress-strain predictions near failure and, hence, aid the search for a universal failure criterion.

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References

1. G Dean and L Crocker, The Use of Finite Element Methods for Design with Adhesives, NPL Good Practice Guide No 48, National Physical Laboratory, 2001.
2. G Dean, B Read, L Wright and L Crocker, Proceedings of Structural Adhesives in Engineering VI, July 2001, 171-175.
3. B Duncan, L Crocker, J Urquhart, E Arranz and R Mera, Proceedings of Structural Adhesives in Engineering VI, July 2001, 85-89.
4. ISO 11003: 1993 Adhesives - Determination of shear behaviour of structural bonds - Part 1: Torsion test method using butt-bonded hollow cylinders. Part 2: Thick-adherend tensile-test method, International Standards Organisation, 1993.
5. ISO 15166: 1998 Adhesives – Methods for preparing bulk specimens. Part 1: Two-part systems, International Standards Organisation, 1998. Part 2: Elevated-temperature curing, one-part systems, International Standards Organisation, 1998.