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Accurate and continuous adhesive fracture energy determination using an instrumented wedge test

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ABSTRACT

The wedge test and the related double cantilever beam test are practical methods of assessing structural adhesive fracture energy. In the former, and to a lesser extent the latter, a recognised problem is the difficulty of following the length of the growing crack, required to calculate fracture energy with any accuracy. We present a novel method of measurement of crack length that has the advantages of being accurate and allowing continuous assessment of crack-length evolution during the failure process. It is based on the attachment of a series of strain gauges to the outer surface of one of the beams constituting the adhesive assembly. Surface strain measurements are interpreted directly using simple beam theory. The method has been validated both with adhesive assemblies under failure conditions and by tests undertaken on "artificial" joints, where "bonding" is effected by clamping adherends together.

1. Introduction

Of the various adhesion tests available for evaluating the fracture strength of structural adhesive joints, the double cantilever beam (DCB) and its close relative, the (so-called Boeing) wedge test, are amongst the most versatile, and generally yield the most reliable information about fracture energy (e.g. [1–11]). With a judicious choice of test geometry, these systems lead to relatively small adherend strains near the crack front [10,11]. As a result, local plastic strain, which leads to supplementary energy dissipation, is relatively limited. The main difference between the DCB and the wedge test is that in the former, fracture occurs at an imposed *rate of* separation and in the latter, at imposed separation. (The DCB also tends to be used with thicker adherends.) Two adherends are bonded along (most of) their length and with the DCB, a force is applied to each (for example in a tensile testing machine), at the open end and perpendicular to the joint, in order to force debonding [2]. The separation rate of the two points of application of the force is maintained constant. If the length of the opening crack (either within the adhesive or at the interface adherend/adhesive, depending on type of failure) is represented by a, it may be shown that the energy release rate, equivalent to fracture energy, G_c, follows a scaling rule of the form $G_c \sim a^2$. Beam analysis based on the opening displacement and the force applied allows a, and therefore G_c, to be evaluated.

However, since the bending moment leading to failure increases linearly with a, at constant applied force, crack growth may accelerate and become unstable in certain cases. This problem has been countered by the development of the more refined, *tapered* double cantilever beam (TDCB) test, in which stability is restored by using profiled adherends with thickness increasing away from the region of force application (e.g. [4,12]). (Also, in principle, crack length need not be measured directly.) Notwithstanding, it is not always convenient, or even possible, to use profiled adherends (for instance, when testing the adhesion properties of automotive body assembly materials) and so an alternative set-up is the so-called wedge test, which uses the same geometry, generally of thin plates bonded together, but the opening displacement is maintained constant by insertion of the "wedge" [11]. Crack growth is then "driven" by the restitution of stored, elastic, strain energy stored in the bent adherends, mainly from the wedge up to the crack front [13]. A considerable advantage is that the scaling relation becomes $G_c \sim a^{-4}$, leading to stable crack growth at decreasing rate [14,15]. The disadvantage is that, since the force exerted on the adherends by the wedge is unknown, direct measurement of the crack length, a, is necessary to calculate G_c.

Adherend lengths are typically of the order of 10 cm, and wedge thickness of the order of a few millimetres, and as a consequence, the relatively small curvature of the beams means that the evaluation of crack length may be delicate. Various techniques have been used to study crack lengths in adhesion tests. The most basic techniques rely on direct, or microscopic, observations of the position of the crack tip, sometimes with the

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addition of paint, or other marking fluid, to the joint edges to facilitate observation [11,15–17]. Use has been made of optical correlation [15], laser moiré [18] and speckle interferometry [14]. Electrical techniques have also been tried, such as measurement of crack growth through changes in electrical resistance of carbon paint applied to the edges of non-conducting substrates [19], or by employing piezoelectric techniques [20]. The use of a single strain gauge technique has also been reported [21]. Displacement sensors have been employed for continuously monitoring cracks [11]. Measurement of crack length nevertheless remains a delicate process in many practical cases. In the present contribution, we present a novel method making use of strain gauges attached to the adherends along the direction of crack propagation. By combining the data from the various strain gauges in their different relative positions with respect to the crack front, an accurate, and potentially continuous, assessment of crack length can be obtained. Although the technique of attaching strain gauges to the opposite side of an adherend (from that which is bonded: the "back face") has already been used, previously the joint geometry was generally rather different [22–27].

2. Experimental

2.1. Materials

Wedge adhesive test assemblies were constructed from aluminium plates, bonded together using an epoxy adhesive. The system chosen was "asymmetric", in that the two adherends to be bonded were of different thicknesses. Aluminium plates of alloy 2024, of Young's modulus, E, and Poisson's ratio, ν, respectively, of ca. 70 GPa and 0.33, were obtained from sheets of thickness 5 and 1.6 mm, the latter being clad. These represented, respectively, the "rigid", or thick, and the "flexible", or thin, adherends. Relative flexural rigidity is governed by the ratio of the cubes of thickness (for the same Young's modulus), thus giving a figure of ca. 30. The terms "rigid" and "flexible" are therefore reasonable.

Adherend lengths were 150 mm ("rigid") and 110 mm ("flexible"), and their relative positions, after bonding in a jig, were as indicated in Fig. 1, with a joint width, b, of 25 mm. The (initially) unbonded zone on the right corresponded to that of three of the strain gauges, for reasons described below, and also to facilitate insertion of the wedge. The adhesive used was a commercial epoxy resin consisting of bisphenol A of average molecular weight <700 cured with N(3 dimethylaminopropyl)–1, 3 propylenediamine. Crosslinking was effected at ambient temperature (ca. 20 °C) for 24 h under 2 bar pressure and at ca. 55% RH. Bondline thickness was maintained at ca.0.35 mm (measured by optical microscopy), by inserting PTFE spacers at the two point extremities before crosslinking. The constancy was checked by optical microscopy.

The main aim of this contribution is to report a new development for measuring strain, and thus obtain crack length

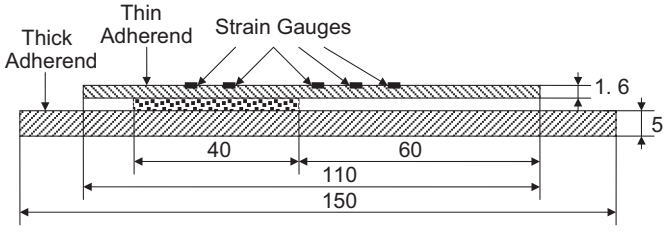

Fig. 1. Representation of geometry of asymmetric wedge test sample (dimensions in mm).

in the wedge test, and to corroborate results we have employed two different surface preparations of aluminium prior to bonding. Both aluminium surfaces to be bonded in a given joint were prepared in an identical manner, either by simple abrasion or by an electrochemical treatment. For both types of preparation, the initial procedure was surface degreasing with detergent solution, drying in hot air, rinsing in acetone, followed by light abrasion/polishing with 1200 grade emery paper. In the case of the simple abrasive treatment, this was followed up by abrasion with 400 grade emery paper and distilled water rinsing, drying in hot air and rinsing in acetone.

In the case of the electrochemical treatment, after the light 1200 grade emery abrasion, further detergent cleaning, hot air drying and acetone rinsing preceded immersion in an electrochemical bath. Phosphoric acid anodisation (PAA) was adopted, using a solution of 10% (by weight) of phosphoric acid (H_3PO_4) in deionised water, under a 10 V direct current potential for 20 min at ca. 20 °C [28]. The aluminium served as the cathode and a titanium anode was used. After treatment, surfaces were rinsed in distilled water, hot air dried and finally acetone rinsed.

Examples of the final surface topography of the simply abraded and electrochemically treated surfaces obtained by atomic force microscopy (AFM) are shown in Fig. 2. (The apparatus used was a Digital Instruments (Veeco Metrology Group) Nanoscope®.) It is clear that anodisation gives a much rougher, or more "peaky" surface topography.

In some experiments, detailed below, surface preparation was of no importance, since no adhesive bonding was performed; a controllable, "artificial" bonded joint was employed instead.

2.2. "Artificial" wedge test

This technique was employed in order to estimate the accuracy of the strain gauge technique developed here, without using an actual *adhesive* joint. The same aluminium adherends as described above, of thicknesses 5 and 1.6 mm, were employed, but instead of bonding them together with an adhesive, a simple screw-based, collar-like clamping system was devised, which could be slid over the "joint" section, i.e. both adherends were placed together, as though bonded, and secured at a desired value of x, equivalent to "crack length", a (see Fig. 3). The joint would be effectively unbonded for x less than the value chosen and bonded for x greater, x being directly measurable. Strain gauges were bonded in place along the central line of the thin adherend, at values of x of 16, 26, 36 and 46 mm. Strain measurements were taken with two wedge thicknesses, Δ, of 4.6 and 9.7 mm, and three "beam lengths", a, of 64, 75 and 90 mm for $\Delta = 4.6$ mm, and 75, 90 and 102 mm for $\Delta = 9.7$ mm. This technique permitted both the fabrication of "artificial" wedge-type joints, described here, by the clamping of unbonded aluminium plates at a desired value of x, before wedge insertion, and also the "reconstitution" of bonded wedge samples, either partially or totally separated during prior tests, both to corroborate crack-length evaluation and check that plastic adherend deformation had not occurred during a test. However, due to the imposed, straight "crack front" parallel to the y-axis in this technique, any effects due to anticlastic bending, or other phenomena leading to non-rectilinear fracture fronts, are necessarily neglected [14]. Similarly, any possible influence of a deformable elastic foundation ahead of the crack front, or root rotation, is neglected [13,15,29,30].

2.3. Asymmetric wedge test (AWT)

The principal experimental technique used here to estimate crack length, a, depends on the use of strain gauges bonded to a