

Review of Tests for Adhesion Strength

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Abstract

This review discusses potential measurement methods for characterising and quantifying the interfacial adhesion strength properties that are key to the strength of bonded systems. Some approaches for including properties of the interface in design calculations are outlined. Tests for adhesive joints, fracture toughness and engineering coatings are covered. Since the conditions causing initiation of failure are critical, methods for detecting the start of a fracture are discussed. Although there is a plethora of methods available, only a few are capable of providing quantitative data that can be readily used in design calculations.

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INTRODUCTION

The mechanical response of a materials system, such as an adhesive joint, coating or composite, is influenced by the properties of interfaces within the system. De-bonding at an interface is a potential mode of failure in such systems. However, quantitative properties of the interface are seldom considered in the design process owing to the lack of validated data and the absence of design models and tools.

Workers in the adhesives field, such as Sharpe [1] and Bikerman [2], have argued that the statistical improbability of a fracture propagating solely along a molecularly rough surface means that true interfacial failure never occurs. Thus, the phenomenon of 'interfacial failure' is more accurately described as **near surface failure**. However, other authors [3] have argued that failure at the interface can be thermodynamically favoured and that the surface energies can be correlated with bond strength with polar components of the surface energies playing a critical role. Whatever the terminology employed, understanding the behaviour of interfaces throws up many challenges. Stresses in the region of the interface are difficult to determine accurately owing to the difficulty in modelling load transfer between dissimilar materials. The properties of surfaces may differ both chemically and physically from those of the bulk material (e.g. oxide layers on metals). Furthermore, there is some evidence that the proximity of another surface may further modify the properties of interface layers of the adhesive through mechanisms such as molecular re-orientation, preferential diffusion/adsorption of components or altered chemical reactions (e.g. through catalysis or differences in the thermal history during cure). Some workers have used the concept of an **interphase** region to describe material characteristics near an interface [4, 5]. The properties of the adhesive in this region can be significantly different to the bulk adhesive [4-7]. The differences between bulk and interface properties depend on the adhesive, surface material and surface preparation. Some workers have reported substantially higher modulus values for the near surface material, attributed to the transfer of materials from the surface oxide layers into the adhesive [4]. However, others have reported decreased modulus near the interface [5-7] thought to be due to incomplete cure and residual stresses in the near interface region. The extents of the interfacial zones in the adhesive layer have been estimated as relatively thick (greater than 0.1 mm) in comparison to bond thickness [3, 4-7]. The keying of adhesive into surface roughness features can also be considered as forming an interphase region whose properties affect the mechanical performance of the joint [8]. In this review the term interface is used to encompass the true interface, the interphase and the near surface area.

Accurate characterisation of materials at interfaces requires sophisticated instrumentation for measuring at small scales. Many of the high vacuum analysis methods available for chemical analysis of surfaces may not be entirely suitable for characterising interfaces. The development of techniques such as scanning probe and atomic force microscopy offers scope for determining properties at the interface. From an engineering point of view, the most important property could be thought to be the 'strength' of the interface. Whether the mode of failure is due to a true interfacial failure or failure in a layer of material bordering the interface probably makes little difference in an engineering design.

In theory, if all free energies at the surfaces can be quantified then the energy required to fail the interface can be calculated directly. Wettability (and contact angle) measurement techniques enable determination of surface energies resolved into dispersive and polar terms [2, 3, 9, 10] and with the correct choice of probe liquid acidic and basic properties of the surfaces can be quantified. Unfortunately, the surface energy approach has only limited

application to predicting the strength of a joint since, as mentioned above, true interfacial failure is unlikely. Further complications arise since the contact area, due to roughness at a molecular scale, is difficult to determine although adsorption techniques have been used [11]. Furthermore, the surface energy approach ignores any direct chemical interaction between the adhesive and adherend and also fails to consider any changes in the composition of the surface layers due to the presence of the second layer. Wettability is therefore a useful method for assessing suitability to bond but would be difficult to relate directly to bond strength.

An alternative technique for characterising energies of interaction between surfaces is the determination of detachment forces and contact radius using sensitive surface force apparatus [12]. Highly sensitive force measurement systems enable the measurement of extremely small adhesion forces. The measurements require that the surfaces are molecularly smooth. This is generally achieved through the use of cleaved mica sheet substrates. Monolayers of polymer or surfactant can be deposited on the mica surface and interactions measured directly. This type of measurement can yield accurate adhesion strengths but is limited in the types of materials that can be studied through the requirement of molecularly smooth surfaces.

Thus, the approach that will be undertaken in this project will be to develop mechanical test methods that quantify the strength of the 'interface' in order to assess joint strength and evaluate the effects of surface pre-treatment or interface degradation. The purpose of this review is to identify potential tests for the evaluation of interface strength and also approaches that could be used to incorporate adhesion strength in a quantitative finite element (FE) model (to establish what data could be required). The review of methods is divided into the following sections:

- Section 2. adhesive joint test methods (using bonded joint configurations and a maximum strength type analysis),
- Section 3. fracture mechanics tests (where the energies of a growing crack are analysed);
- Section 4. coatings techniques (where only one interface is present);
- Section 5. detection of crack/fracture initiation; and
- Section 6. modelling approaches.

Adhesive joint test methods (including fracture test methods) were reviewed in the Performance of Adhesive Joints programme by Broughton and Mera [13] for their applicability towards durability assessment in hostile environments and under load (static and cyclic). Guidance on performing various tests is given in Good Practice Guides [14, 15]. Coatings adhesion tests were reviewed by Maxwell [16] and the relevance of such techniques for adhesives is discussed in Section 4. The tests in this review are described and evaluated in terms of their capability to measure properties related to interface strength.

For adhesive joint design, avoiding the initiation of a crack is important for service performance. Therefore, in many tests it is important that the formation of a crack can be detected. Methods for establishing the moment of crack initiation and joint failure are discussed.

2. ADHESIVE JOINT TESTS

2 OVERLAP AND SHEAR JOINT TESTS

Lap tests are performed when overlapped adherends are pulled in tension to generate predominantly shear stress within the adhesive layer. This class of tests includes some of the most familiar adhesive joint tests such as the thin lap shear, the double lap shear, strap joint and thick adherend shear tests.

2 Single Lap Joint Tests (thin adherends)

Single lap joint tests, such as the ubiquitous lap shear test [17-32], are relatively straightforward from the specimen preparation and testing perspective. However, these tests have recognised limitations for the accurate determination of joint design parameters. Stresses are concentrated at the ends of the overlap. The directions and magnitudes of these stresses depend on numerous factors:

- applied load and deflection (increasing either leads to an increase in stress);
- mechanical response of the adhesive (elastic or elastic-plastic behaviour)
- mechanical stiffness of the adherends (lower stiffness leads to higher peel stresses) [26]
- geometry at end of overlap (shape of adherend corners, joint fillet) [22, 23, 25, 28]

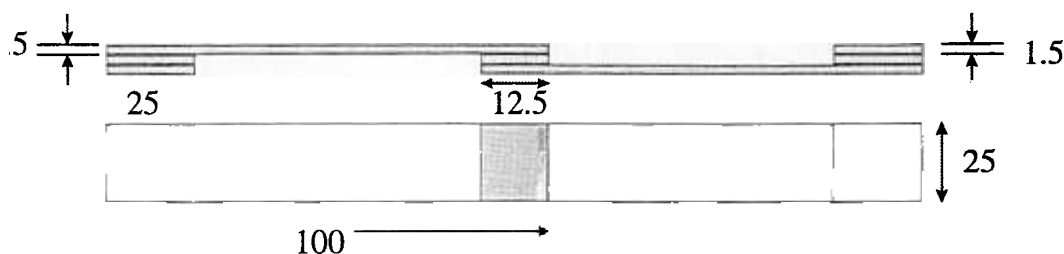


Figure 1 Lap joint specimen geometry

Failure tends to initiate at the end of the overlap, close to one of the adherends (the geometry of the joint at the end of the overlap affects this location). However, the stress state in this region is highly complex. There are some closed-form analytical solutions for stress at the overlap ends [22, 28] but these require idealised geometries and experimental verification has proved difficult to obtain. Finite element (FE) methods can be used to predict stress concentrations for any geometry [23, 25]. However, results can be sensitive to the method of meshing, the materials models may lack accuracy and there are problems interpreting the results at interfaces between materials and singularities. Adherends are sometimes tapered to reduce peel stresses at the end of the overlap.

The geometry of the lap shear joint specimens used by NPL in the PAJ and PAJex programmes [29-32] are shown in Figure 1. The end tabs are bonded to reduce out-of-plane bending in the specimen.

Thick Adherend Shear Test

The thick adherend shear test [33-37] is preferred for determining design parameters as the thick, rigid adherends reduce (but not eliminate) the peel stresses. Typical joint geometries are shown in Figure 2. The state of stress is predominantly shear but there are peel stresses at the end of the overlap. Failure occurs at the end of the bond line and is thus sensitive to the geometry of this region. The locus of failure tends to be close to the adherend and, thus, interfacial failure is a possibility. Cracks have been observed to run along the interface. Higher joint extensions can be realised if the corners of the adherends and the spew fillet are profiled to remove stress concentrations. Stresses at the overlap ends are complex and difficult to calculate analytically, although FE approaches have been used [36, 37].

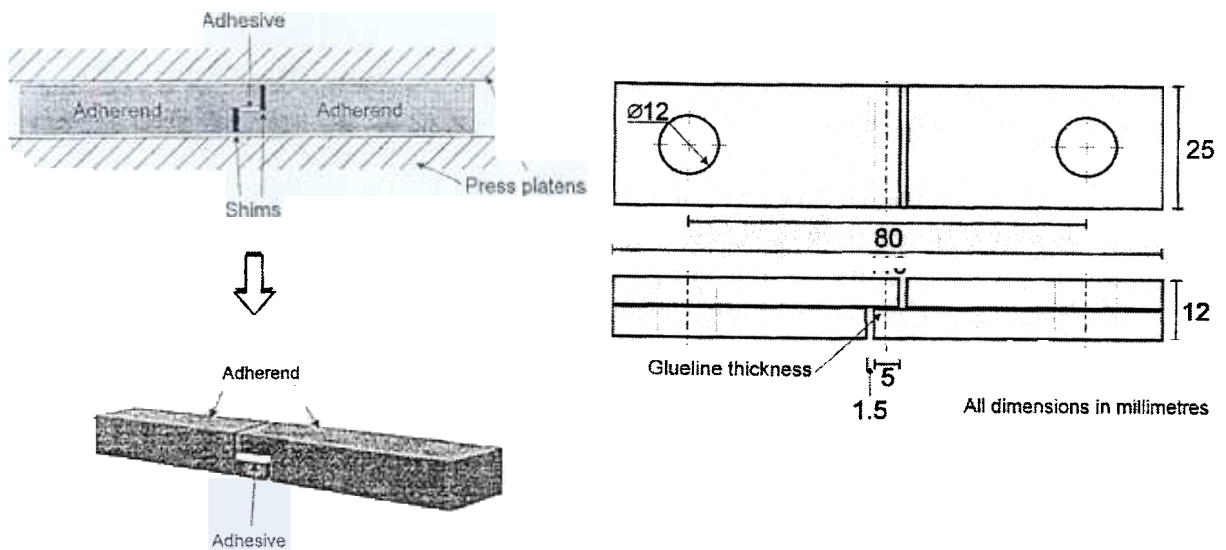


Figure 2: Thick adherend shear test geometries

Double Lap Joint Tests

Attempts to eliminate eccentric loading, responsible for bending of the adherends and rotation of the bonded region, have resulted in the development of a symmetric variant of the single-lap shear test, known as the double-lap joint [38-41]. Figure 3 shows a schematic representation of the symmetrical double lap joint where the central adherend is twice the thickness of the outer adherends. Although bending is reduced peel stress at the outer adherends is unavoidable, since the load is applied to the outer adherends via the adhesive, away from the neutral axis. Additional bending can also be introduced when clamping pressure is applied to the double lap end of the specimen, it is recommended that a rigid spacer be used to minimise this effect. The bending moment introduces tensile stresses across the adhesive layer at the free end of the overlap and compressive stresses at the other end. The centre adherend is free from the net bending moment but there is still an element of peel stress at the ends of the overlaps. The stresses at the joint end are sensitive to the mechanical properties of the adherends, the shapes of the joint ends and the geometries of the adhesive fillets.

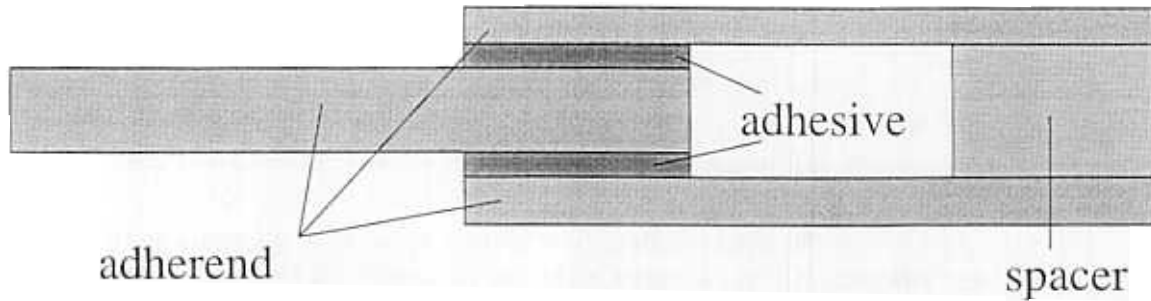


Figure 3: Schematic of double lap specimen

The double lap test removes some of the disadvantages of the single lap test but is more expensive to prepare. There is no absolute requirement for the inner and outer adherends to be of the same material. The location of the stress maximum can be controlled through the shape of the thin adherend ends and end fillets. Hence, this specimen has the potential to test the bonding of adhesive systems to materials that are available as either thick or thin adherends. However, differences in bending stiffness of adherends could complicate the comparison of data determined for different materials.

2.1.4 Strap Joint

The strap joint consists of two thick adherends butted together. Straps (one for the single strap joint or, preferably, two for a double strap joint) are then bonded to the faces of the adherends to carry tensile loads in shear (in test specimens the gap between the butt-ends of the central adherends is free of adhesive). This geometry is also described in ASTM D3528 [38] as an alternative specimen to the double lap joint. The strap joint test reduces bending moments since the specimens are loaded through coaxial adherends. The square ended straps generate significant peel forces at the end of the strap. By tapering the straps peel forces at the ends of the adhesive layers can be reduced further. The tapered strap joint, as shown in Figure 4, can be used to generate adhesive design data [42].

As with other lap joints, the adhesive in the strap joint is predominantly stressed in shear at the centre of the joint with peel stresses at the end of the overlap. However, analyses of the strap joint suggest that a tensile stress concentration is inevitable at the end of the strap. The size and location of the stress concentration depends on the relative stiffness of the adherends and the local geometry at the end of the overlap. The shape of the fillet can determine whether the stress concentration is near the interface with the main adherend or the interface with the strap. This could be used advantageously to characterise the bond strength of an adhesive to either thick sections (central adherends) or thin sections (the straps). There is nothing to forbid the central and strap adherends from being different materials.

2.5 Scarf Joint

The scarf joint, Figure 4, can be thought of as an 'angled' butt joint. When pulled in tension a mixture of shear and tensile stress is generated in the adhesive layer. The proportions of shear and tension stress can be varied by varying the scarf angle [42-45]. A scarf angle of 90° to the axis of the specimen is a butt joint where tension dominates. An angle of 0° to the axis of the specimen is a lap joint where shear dominates. Scarf joints with lower scarf angles have higher strengths owing to their greater bonded areas and reduced tensile peel stress. The scarf angle and detailed geometry at the tips of the scarf sections influence the location of the stress maximum, near the interface that initiates failure [44, 45]. The stress state at the stress concentration is complex and it is not obvious that this test could be used to quantify adhesion strength.

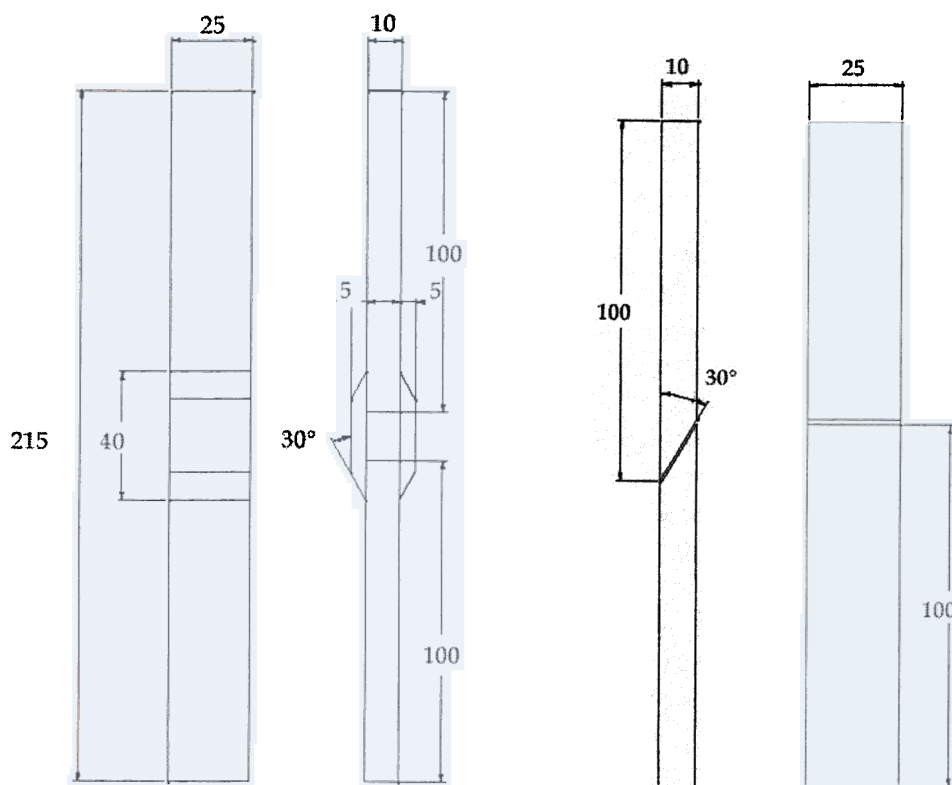


Figure 4: Tapered strap and scarf joint specimens

2.1.6 Other Shear Tests

There are many other test methods that impose shear stress on the adhesive layer. The butt and napkin ring torsion tests are known to provide a very uniform shear stress in the adhesive layer with minimal peel stresses [46-48]. Shear strains to failure determined for adhesives in these tests can be much greater than those determined in other tests. Torsion tests, which require test machines capable of applying torque, are less common than tensile test machines. Facilities are also required in order to prevent axial loading in addition to torsion. Failures seen in torsion tests have generally tended to appear to be cohesive in the adhesive rather than interfacial [48].

Pin and collar tests [49, 50] also test adhesives in shear. Specimens are easy to prepare and testing is straightforward to perform by pushing the pin from the collar. However, there has been little investigation of the stress distribution in such specimens. A major concern is the possible sensitivity of results to the degree to which the pin is 'centred' in the collar.

Joint specimens tests based on bulk specimen shear tests such as the Arcan or Iosipescu tests can also be carried out on adhesives [51]. Failure will tend to initiate at a stress concentration at the end of the bond. The block shear test [52] is another possible method for testing adhesives but has found little favour owing to difficulties in interpreting and correlating results quantitatively.

2.2 PEEL TESTS

2.2.1 T-Peel

The T-peel test [53-55] is commonly used to assess the resistance of adhesive systems to normal force peel loading. The T-peel specimen is shown in Figure 5. The test requires flexible adherends i.e. those that can be bent through 90°. Tests are performed under constant separation speeds in a standard tensile test machine. The measured force-extension curve yields the maximum force and the peeling force (for steady state crack propagation). The test is quite often used for durability assessment and in these tests the peeling force is used to assess the bonding system. Work at NPL [55] suggests that the peeling force can be relatively insensitive to environmental degradation and that the maximum force is a much more sensitive indicator of joint performance.

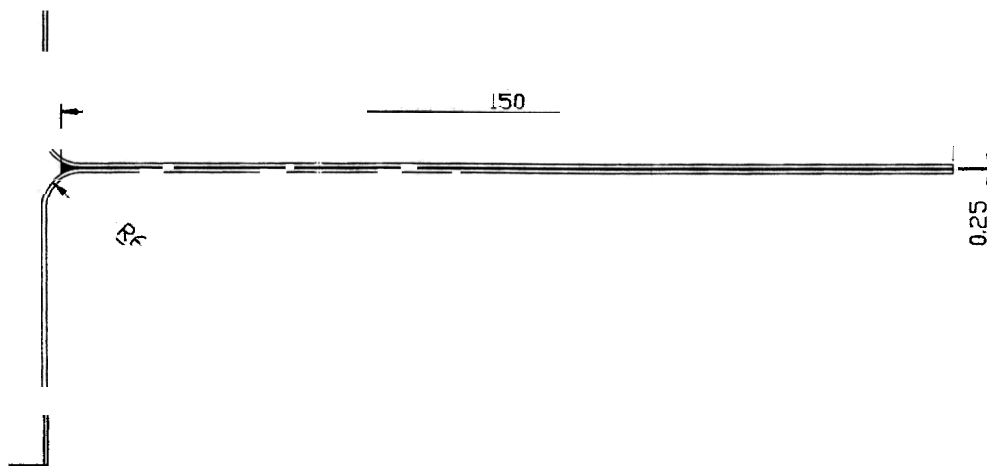


Figure 5: T-peel specimen

The T-peel joint performance is dependant on joint materials and geometry. Most of the deformation in the test occurs in the adherends. Therefore, the thickness, stiffness and plastic yield strength of the adherend material have major influences on the test results. The adherends bend during the test, changing the stress distribution. The degree of fillet in the joint

influences both the strength and location of initial failure. The flexibility of the adhesive can alter the location of the stress maximum. With rigid adhesives, such as an epoxy, the stress concentration is at the end of the fillet. In the case of more flexible adhesives, such as a polyurethane [44] or 'moist' epoxy [55], the stress concentration is inside the fillet. The locus of failure and propagation route of the crack can vary between the interface and centre of the adhesive layer.

The evidence suggests that the T-peel test is unlikely to provide accurate interfacial strength data for design purposes. The crack propagation may not necessarily be along the interface. The maximum load born by the joint is sensitive to many factors; in particular the local radius of curvature and peel angle of the adherend near the crack tip, and it is difficult to relate to a material or interface property.

2.2.2 Flexible to Rigid Peel Tests

There are several peel tests for assessing the bonding of a flexible adherend to a rigid adherend [56-71]. The main differences between the methods are the angles of peel and whether the peel angle remains constant during the test. Much of the energy is dissipated in the adherends rather than the adhesive. Accurate data on the elastic-plastic mechanical properties of both the adhesive and the adherends are important in the analysis of the test data [67-69]. Peel tests tend to be used to a greater extent for characterising flexible adhesives (including pressure sensitive adhesives) than they are for rigid structural adhesives. Peel strength is often quoted on adhesive data sheets. For structural adhesives the T-peel test is most often quoted.

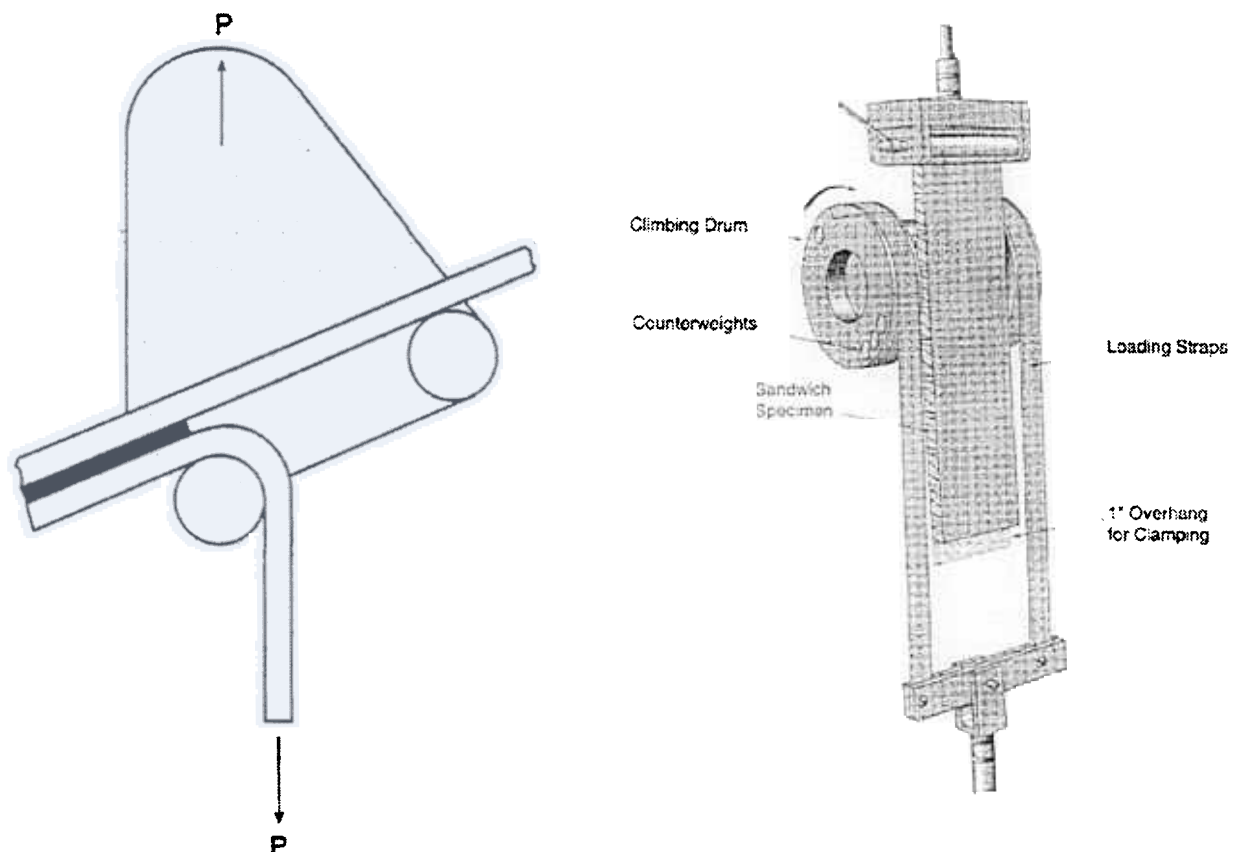


Figure 6: Floating roller and climbing drum peel tests

The 180° peel test [57, 58] requires that one flexible adhesive is sufficiently flexible to be bent back through 180° before being stripped from a more rigid adherend at a constant peel rate. The average load per unit width to peel the specimen is determined. This test seems to be favoured for non-structural adhesives, e.g. pressure sensitive adhesives and tapes.

The floating roller test method [59-62], shown in Figure 6, also determines peel strength of a flexible-to-rigid bonded assembly. The roller mechanism enables a constant angle of peel to be maintained throughout the test. The test fixture can be adjusted to vary the peel angle. The average load obtained during stable peel is recorded as a characteristic of the bond.

A further standardised peel test is the climbing drum peel test [63, 64]], shown in Figure 6, used to determine the bonding of sandwich structures. The drum fixture is used to peel the flexible skin from the rigid structure at a constant peel angle. Once again the average peel load is measured. This method appears to be used mostly in the aerospace industry.

Peel tests, while providing useful comparative data, are unlikely to provide quantitative measures of interface strength. There is no guarantee that the fracture path will be along the interface. Stress distributions depend significantly on local geometrical features such as crack sharpness and peel angle. Other than the aerospace industry, these tests seem to have found little favour in industry for generating data for the design of structural bonds. The conversion between peel load per unit area to stress requires assumptions about the extent of the peel zone that are likely to be inaccurate.

2.3 TENSION PULL TESTS

These tests determine the adhesion strength from the force required to pull an adhesive off a surface (or a part from a surface). Pull-off tests are used to test adhesion and cure of adhesives and coatings. Micro pull-out tests, used to assess resin-fibre adhesion in composite systems, may have applications for assessing larger systems.

2.3. Pull-Off and Butt Joint Tests

The butt joint test [72-77] is a severe test of an adhesive as the adhesive experiences high levels of tensile and hydrostatic stress. The butt-joint specimen is prepared by bonding two rods or bars of equal cross-section together end-on. The joint is pulled in tension to obtain the butt tension strength. A schematic of this test is shown Figure 7. Although appearing straightforward to perform, obtaining reliable and accurate data from this test can be challenging. Alignment of the bonded specimen and the applied force is critical to avoid bending/peel stresses and obtain the 'true' butt tension strength. Procedures have been developed at NPL [77] that virtually eliminate alignment errors in the test. However, the remaining non-uniformity of the stress distribution still causes problems in interpreting the maximum stress in the adhesive [75, 76]. It is possible that the specimen could be profiled in some way to produce a more uniform stress distribution. Such an approach, using a profiled dolly, may also be applicable to the pull-off test.

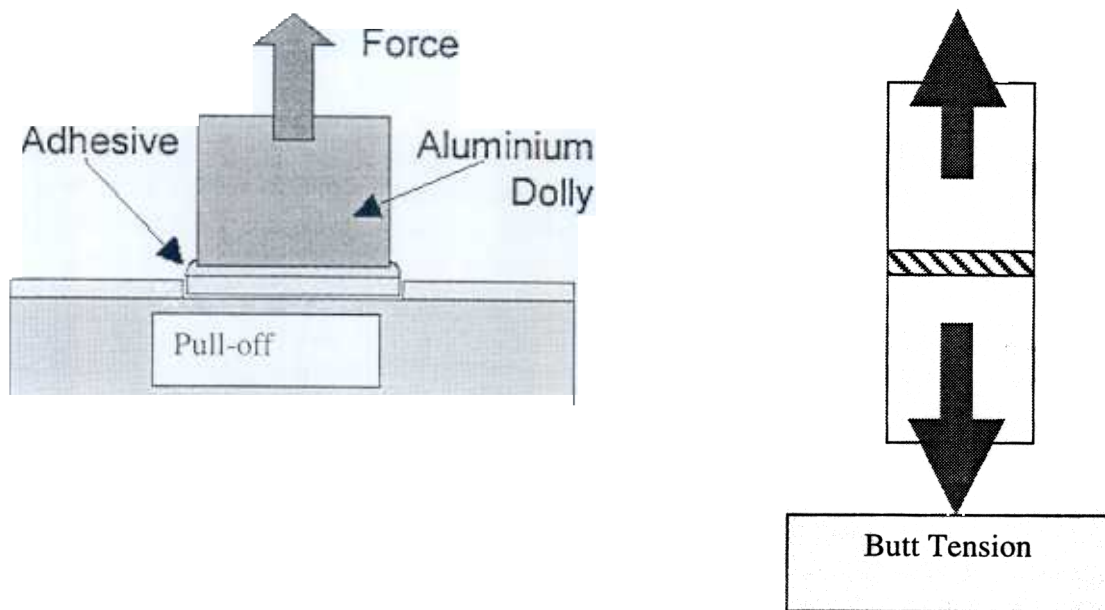


Figure 7: Tension pull-off and butt joint test methods

The pull-off test [78-81] is very similar in application to the butt-joint tension test. A typical tensile pull-off test that can be used with either coatings or adhesives is shown in Figure 7. A cylindrical dolly (typically aluminium) is bonded to the coating being tested. For an adhesive test the dolly would be bonded directly to the surface of interest. The substrate is immobilised through clamping and the dolly pulled-off normal to the surface. The maximum force is recorded and used to determine the failure stress.

This test commonly used in the construction industry to assess the development of bond strengths since it is simple to perform and can be carried out *in-situ* (either vertically or horizontally) on virtually any type of surface [81]. There are commercial instruments available to perform pull-off tests.

The main sources of error in this test result from minor misalignments of either the specimen or the applied force that introduce bending/peel forces to the adhesive layer. The resulting 'cleavage' stresses concentrate at an edge of the specimen and reduce the measured strength. As with all adhesive joint tests, the stress-distribution will be non-uniform and the results sensitive to the local geometry of the specimen. It may be difficult to control the shape and size of the fillet at the edge of the dolly. A further source of concern is that failure will occur at the weakest point of the joint – this may not be at the surface of interest. The maximum stress that can be applied may be limited by the cohesive strength of the adhesive or the strength of the adhesive-dolly bond. In such a case, the test would give a minimum adhesion strength for the system.

2.3.2 Pull-out tests

Pull-out tests [82-85] have been used to assess bonding of small components (e.g. glass fibres) to large components (e.g. pipes). Pull-out specimens have tended to be cylindrical rods or fibres embedded within a block of adhesive or within a coaxial arrangement. The specimen is loaded to pull the embedded specimen from the adhesive. In the fibre pull-out test, it is often assumed that the start of fracture can be ascertained from inflections in force deflection

measurement. Once fracture has initiated there is a risk of friction between the fractured interfaces adding to measured forces. Thus, the test will not provide fracture toughness data.

The stress is primarily shear along the interface although the distribution is non-uniform. The tensile stress on the embedded component and shear stress along the interface vary with the embedded depth. The stress is a maximum at the free end of the fibre and decreases to zero at the end of the embedded length. Various closed form analytical (e.g. shear lag analysis) and finite element analyses have been performed to calculate these distributions. There are some uncertainties in the value of maximum stress, particularly when plasticity becomes an issue. However, local strain measurements using Raman microscopy or photo-elasticity have enabled a degree of validation of the stress distributions [85]. Normal forces will also occur due to the singularity at the end of the embedded length and Poisson's contractions of material under stress.

In the pull-out test the locus of maximum stress will be at the interface. Hence, the test will provide information on the adhesion strength of the system. Analytical tools exist for calculating the peak stress. Specimen preparation and testing appear relatively straightforward for macroscopic samples. Therefore, there may be some value in investigating this test further for adhesion strength testing.

3. FRACTURE MECHANICS

Fracture mechanics tests [13, 86-103] provide information on the growth of a fracture within a material. The quantities determined through fracture mechanics tests are the stress intensity factor (K) and the strain energy release rate (G). The stress intensity factor is related to the geometry of the test specimen but the strain energy release rate ought to provide material properties. Analysis methods for bulk material fracture tests are well established, particularly for elastic materials. However, techniques for multi-material systems and materials that experience plastic yield are less well established, although theoretical developments are occurring to account for plastic zones [99] and rate/temperature dependence [103].

Fracture mechanics tests have been applied to adhesives. The common test methods are based on the double-cantilevered beam (mode I) and end notch flexure (mode II) tests. Mode I (crack opening tests) tests impose severe cleavage stresses on bonded joints. Fracture tests require an initial notch or pre-crack. The precise geometry of this notch will influence the results and is a source of uncertainty or variability in the tests. Notch geometry will have more effect on the initiation of crack propagation. Results from the initial part of the test are normally excluded from analyses with G determined from the regions of steady state crack growth.

Fracture mechanics data can be used to predict the strength of adhesive joints; some approaches are discussed in Section 6. However, the prediction process requires the assumption on an existing crack or flaw in the joint. Iterative processes are used to calculate the size of such flaws from joint tests for use in the analysis of bonded structures. The requirement of an assumed flaw size in any calculation has inhibited the uptake of fracture approaches for industrial design purposes. However, fracture tests are commonly performed to assess joint performance in hostile environments and results show sensitivity to the bonded surfaces.

3.1 WEDGE CLEAVAGE TEST

The wedge cleavage test [13, 87-94], commonly referred to as the Boeing wedge test, uses the introduction of a wedge between two flat surfaces to force the adherends apart and impose cleavage stresses in the region of the crack tip, as shown in Figure 8. The wedge imposes a fixed displacement to the adherends and the crack opening force is driven by the elastic stored energy in the adherends. Crack length is monitored with time. The wedge test is simple and cheap to perform. No test machine is required since it is self-stressed. The stressed specimen can be exposed to hostile environments and the presence of chemicals at the crack tip can be expected to accelerate degradation much more effectively than in tests where these species have to diffuse into the bond layer. Commonly a crack growth limit is reached within several days making this test attractive for rapidly assessing durability. This test is considered a reliable method for assessing the environmental durability of adherend surface preparations.

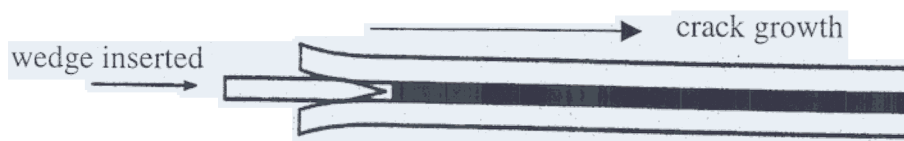


Figure 8: Wedge cleavage test (Boeing wedge test)

Fracture energies, G , can be determined from the crack length, a , wedge displacement, w , adherend modulus, E , and adherend thickness, h :

$$G = \frac{Ew^2h^3}{16} \left[\frac{3(a + 0.6h)^2 + h^2}{(a + 0.6h)^3 + ah^2} \right] \quad (1)$$

The accuracy of the fracture energy determined can be compromised by plastic deformation of the adherends (reducing cleavage forces) and adhesive. This test is not considered particularly accurate for fracture toughness measurements. The driving force depends on wedge insertion distance and the stiffness of the adherends. Although specimens can be manufactured with the initial crack at the interface there is no certainty that the crack will continue to run along the interface. FEA suggests that the regions of maximum strain and stress in the specimen, prior to crack propagation, are close to the interface.

The wedge test has been used to assess the durability of adhesive systems. Published results suggest that the test can distinguish between different surfaces and surface pre-treatments [89-94]. The test appears to offer crack growth results that depend on the properties of the interface. This simple test appears to offer a means of discriminating between surface treatments.

3.2 MODE I TESTS

3.2.1 Compact Tension Test

In the compact tension test [95] shaped adherends are bonded together to produce a test specimen with the same geometry as the solid compact tension specimen, Figure 9. Specimens are 25 mm wide with a 25 mm long bond line. The depth of adherend is typically 12 mm at either side of the bond line. The specimen is loaded at one end of the bond producing a peel force. The test is run at a constant loading rate or crosshead speed until the joint is completely failed. The maximum load is recorded.

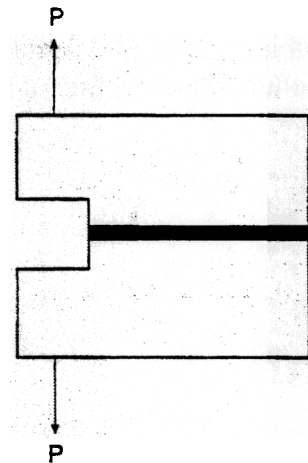


Figure 9: Compact tension joint specimen

3.2.2 Double Cantilevered Beam

The double-cantilevered beam (DCB) test [97], Figure 10, is used to measure the initiation and propagation energy of a mode I crack. The critical strain energy release rate or fracture toughness, G_{IC} , depends on crack length and is calculated:

$$G_{IC} = \frac{4P^2(3a^2 + h^2)}{Eb^2h^3} \quad (2)$$

where P is the applied load, E is the Young's modulus of the adherend, b is the specimen width, a is the crack length and h is the adherend thickness. Specimen preparation is straightforward. Thick adherend parts can be bonded and tested directly. Where the beams are formed from thin sheet material end tabs need to be attached to allow the beams to be gripped. The dependence of specimen compliance and strain energy release on crack length adds to the complexity and reliability of carrying out and analysing this test.

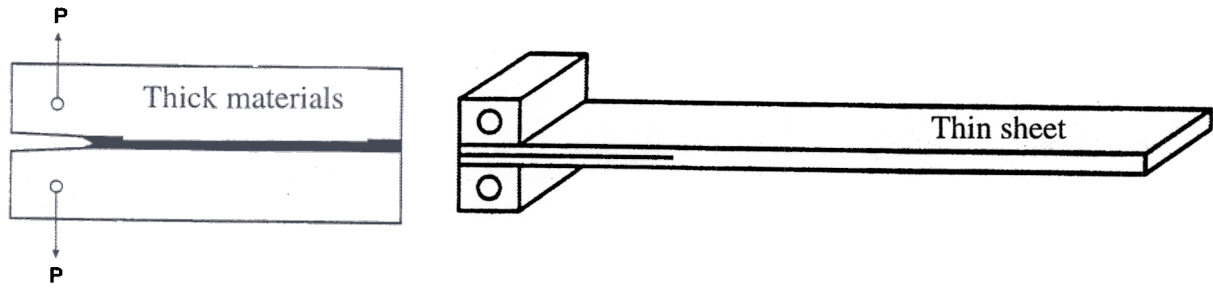


Figure 10: Double cantilevered beam (DCB) test

Specimen compliance can be made independent of crack length by tapering the cantilevered beam, as shown in Figure 11. The tapered double-cantilevered beam (TDCB) test [13, 98, 100] relates compliance to load, width, adherend modulus and bending moment, m :

$$G_{ic} = \frac{4P^2}{Eb^2}m \quad (3)$$

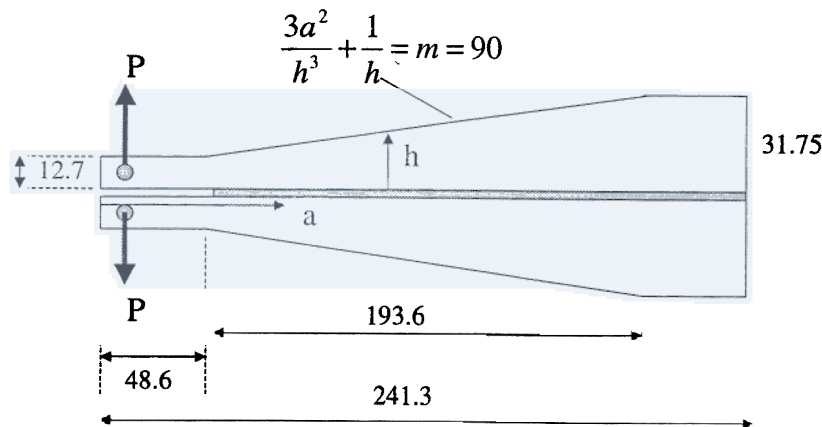


Figure 11: Tapered double cantilevered beam (TDCB) test specimen

The taper height is chosen such that m is constant with crack length from the relationship:

$$m = \frac{3a^2}{h^3} + \frac{1}{h} \quad (4)$$

Although TDCB adherends and specimen fabrication are more expensive than the DCB specimens, the testing is much more routine and, provided that the adherend materials have high yield stress, the adherends should be reusable. TDCB tests have been used to assess environmental durability. As with all fracture tests, information on the strength of the interface can only be obtained if the crack propagates along a surface.

3.3 MODE II TESTS

End Notch Flexure Test

Figure 12 shows the end notch flexure (ENF) specimen [100], which is essentially the double-cantilevered beam specimen loaded in three-point bend. This test characterises mode II (in-plane shear) fracture toughness. For small displacements (and negligible transverse shear deformation), strain energy release is calculated:

$$G_{IIc} = \frac{9P^2 a^2}{16Eb^2 h^3} \quad (5)$$

The ENF test is being developed as a standard method for mode II fracture toughness. Mode II data are important for predicting the behaviour of loading situations where mode I does not dominate.

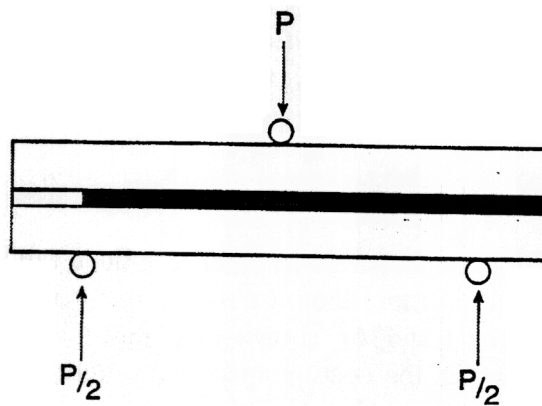


Figure 12: End notch flexure specimen

MIXED-MODE TESTS

Two test methods, mixed mode flexure and cracked lap shear, have been developed to assess fracture toughness of adhesives under mixtures of cleavage and shear stress [101, 102]. The ratio of modes (cleavage to shear stress) can be altered through alterations to the adherend geometries (principally bending stiffness) and the design of the test fixtures. These tests are not considered suitable for characterising interfacial strength owing to the difficulty in characterising the contributions from different fracture modes.

4. COATINGS TESTS

Engineering coatings, like adhesives, must adhere to surfaces. Coatings cover a wider range of material types than adhesives and, therefore, there are many tests that have been developed, some of which may be suitable for adhesives. A review of coatings adhesion tests has recently been issued by NPL [16]. Much of the information in this section has been extracted from this document but with additional comments assessing the application of the methods to adhesives.

The layer thickness of a coating is generally less than an adhesive bond line. Often coatings are deployed as multi-layers and adhesion between layers is equally as important as the adhesion of the base layer to the substrate. Many coatings, particularly thermal barrier coatings, are brittle oxides whose mechanical performance will be very different to ductile polymeric adhesives. These differences need to be considered when assessing coatings methods for characterising adhesives.

Many coatings tests are 'scratch-type' tests where the coating is mechanically damaged and the extent of de-bonding is used as a qualitative test for the adhesion of the coating. Such tests have very little applicability to adhesives and do not provide any data for quantitative prediction of joint strengths.

4 BEND TESTS

Bend tests involve bending the substrate in order to induce failure in the coating. Many tests are qualitative and indicate no more than a pass/fail result for a coating. Instrumented tests, such as the four-point bend test [16], shown in Figure 13, can provide information on the deflection or load under which the coating specimen failed. The mode of failure depends on the mechanical properties of the coating. Brittle coatings may fail due to tensile stress induced in the coating. More ductile coatings will tend to fail through delamination.

Bend tests can provide quality control data or data for comparing surface treatments/coatings. The open face of the coating allows rapid diffusion of chemical species to the interface during environmental exposure experiments. From this perspective, bend tests represent a useful means of accelerating the ageing of an interface to determine material compatibility. One bend test in use by the adhesives community is a three-point bend test [104-106]. A thick block of adhesive is cast onto the centre of a thin, flexible adherend (the standard specifies steel). The load is applied to the adherend opposite the adhesive, bending the substrate. Eventually the peel stresses on the ends of the adhesive block cause the bond to fail. The load-deflection curve to failure is measured. The adhesive block can provide sufficient reinforcement to the adherend that the initiation of failure is obvious from the shape of this measured force-extension curve. However, the ISO 14679 standard test has a number of disadvantages that reduce its general applicability. The standard specifies a 4 mm deep block that can be difficult to prepare with many kinds of adhesive. If the adhesive is tough or flexible then it may be difficult to induce failure. One means of overcoming these limitations would be to bond a rigid block to the free side of the adhesive to increase peel forces in the test. Interpretation of the test results requires calculation of the stress in the adhesive. Linear beam theory may provide some estimation of the failure stress.

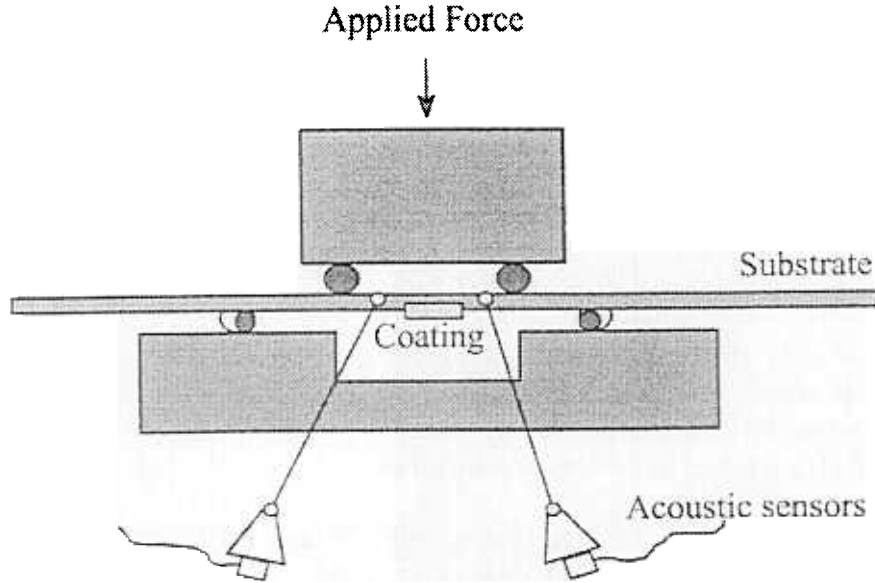


Figure 13: Four-point bend test for coating adhesion

4.2 INDENTATION TESTS

Adhesion of coatings can be assessed qualitatively through hardness tests, such as Rockwell or Vickers [16, 107-109]. The radius of coatings delaminated after indentation is compared with the depth of indentation in order to classify the adhesion of the coating, Figure 14. There have been some fracture mechanics analyses of this type of test. However, the interpretation of such data is complicated. There are several types of failure mode that can occur in the tests. Failure is not necessarily interfacial but can occur in the bulk of the coating. There has been little theoretical analysis of the critical failure conditions occurring at large deformations, likely to occur in the case of flexible or toughened adhesives. Stresses in the coating are assumed to depend on applied load, coating properties and the geometry of indentation. The ratio of indent depth (determined from contact radius r for the Rockwell (ball) indenter or indent half-diagonal b for the Vickers (conical) indenter) to coating thickness h is an important parameter in the interpretation of the results.

Ritter [107] defined three modes of failure in indentation tests:

I Elastic Failure - de-bonding occurs whilst deformation in the coating remain elastic. Interpretation is reasonably straightforward from the measured load, elastic properties of the coating and geometry of the indentation contact.

$$P = \pi r^2 G f\left(\frac{r}{h}, \nu, R\right) \quad (6)$$

A critical shear stress τ_c for de-lamination can be estimated from:

$$\tau_c = \frac{P_c}{\pi r_c^2} f\left(\frac{r_c}{h}, \nu\right) \quad (7)$$

II Plastic Failure – de-bonding occurs after the coating underneath the indenter has yielded. This is a more complex situation to analyse and assumptions have to be made about both the size of the plastic zone and the material properties of the coating following plastic yield. The critical shear stress is assumed to depend on contact geometry and coating hardness, H^C . For the Vickers test:

$$\tau_c = H^C f\left(\frac{b_c}{h}, \nu, k\right), \quad H^C = \frac{P_c}{2b_c^2} \quad (8)$$

III Failure after Penetration of the Substrate – de-bonding does not occur until after the indenter has penetrated the coating and indented the substrate. The load is shared between the coating and substrate. The calculated critical shear strength depends on the contact geometry and mechanical properties of coating and substrate.

Ritter [107] reported interfacial shear strength (IFSS) data for a number of adhesives on glass determined using both Rockwell and Vickers indentation tests. IFSS results were considerably higher than results obtained from lap shear tests, although the lap shear results reported look unreliaibly low. The highest IFSS results were obtained for systems where the failure was type III with the next highest results coming from type II failures. The adhesives were described as polyimide and urethane acrylates, respectively. Although no mechanical properties were given for the adhesives it is very likely that these are high toughness materials with non-linear mechanical properties. One suspicion is that the analyses performed significantly overestimated the stress in the adhesive if the non-linearity was not accounted for correctly.

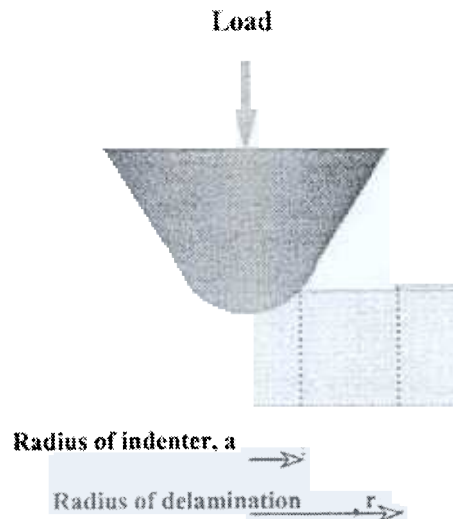


Figure 14: Schematic of a coatings indentation test

Engel [108] presented data determined in type III indentation tests and proposed that a critical de-bond strain be used to characterise the interface strength. This de-bond strain was determined from the point in the test where the rate of de-bond strain accelerated.

Other indentation tests, such as micro- or nano-indentation, may provide more usable information on the mechanical properties of the near-surface material. However, further

theoretical development may be required to interpret the results for elastic-plastic and visco-elastic adhesives.

4.3 BLISTER TESTS

The blister test [110-112] involves pressurising an adhered film through an orifice to force it away from the substrate, as shown in Figure 15. Pressure can be applied by either fluids or gases. The pressure lifts the coating away from a circular release area that constitutes an initial crack of radius a . At a critical pressure and blister height the interface can no longer sustain the stresses and the de-lamination radius will increase. The initiation and rate of de-lamination are used to assess adhesion strength. Fracture mechanics analyses can be used to calculate fracture toughness. These calculations are based on treating the blister as either a membrane or a plate depending on whether membrane or bending stresses dominate [111]. Results will depend on the mechanical properties and thickness of the coating. Cohesive failure of the blister is possible if the adhesion strength exceeds the burst pressure of the coating. Variations on the standard circular specimen and orifice set up have been proposed to produce higher fracture energies and calculable strain energy release rates [110].

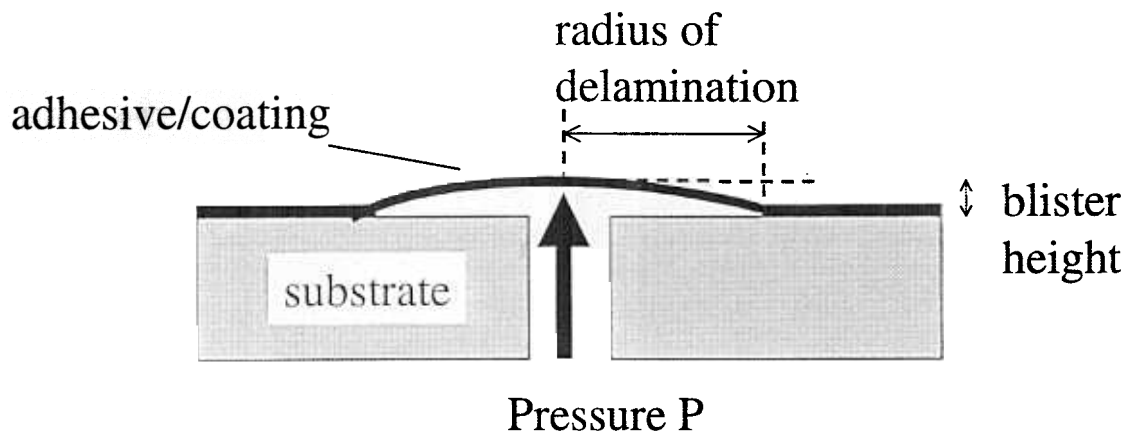


Figure 15: Pressurised blister test

4.4 SCRATCH AND ABRASION TESTS

Scratch and abrasion tests provide qualitative information on adhesion of coatings. In these types of test the coating surface is damaged and adhesion strength is inferred from the subsequent removal of the coating. These tests could, in theory, be used to assess adhesion of adhesive layers but will not provide quantitative measurements of bond strength. Typical scratch and abrasion tests are summarised in Table 1.

Table 1: Scratch and Abrasion Tests

Method	Features	Comments
Ball Cratering (DD ENV 1071-2:1994)	Steel ball rotated against coated specimen in the presence of an abrasive slurry. The wear scar is assessed to determine coating thickness and delamination examined.	More suited to hard or brittle coatings than polymeric adhesives.
Knife Test	The force required to detach a coating from a substrate, by drawing a loaded knife across the coating, is determined.	Used with thicker, softer coatings. Results tend to be used for comparative purposes.
Pressure sensitive tape test (ASTM D3359)	A cross-hatch is scored on the coating. A pressure sensitive tape is applied to the scored area, pressed down and then removed rapidly. The surface and tape are examined to determine the extent of coating removed from the surface. The presence of coating on the tape will lead to the coating system failing this test.	Results will be sensitive to the strength of adhesion between the tape and coating and the manner in which the coating is scored. A comparative QC test only.
Scratch test	A diamond stylus is loaded against the samples and drawn across the surface to cause a scratch. Load can either be constant or ramped. Damage patterns are correlated with measurements such as acoustic emission and friction forces to derive critical loads for various failure mechanisms.	Interpretation of scratch pattern can be difficult.
Shot Peening (BS 2829)	Steel shot is impacted against coated samples for a fixed time. The surface damage is inspected visually and a pass/fail awarded.	Qualitative QC test.

5. DETECTION OF FAILURE

Work on testing adhesive joints shows that, in many cases, joint failure initiates before the ultimate extension or load of the joint is reached [44, 45]. Designing for a long-term service life requires that joints never be loaded to the extent that these failures can initiate (whether through cohesive rupture or adhesive failure). Therefore, identification of the failure initiation point is a critical part of any joint test. By knowing this point, analyses can be performed to calculate stress and strain distributions immediately prior to the initiation of the crack. At the more easily identified point of maximum load in the test, a fracture will be present in the bond that will introduce inaccuracies in any analyses.

This section outlines methods that have the potential to provide an indication of the point in the test where a fracture in the adhesive or de-bond at the interface first occur. There are many techniques that could be considered for this task. This section briefly describes some of the methods that are most likely to prove useful. As with all measurement techniques, there will be accuracy, precision and calibration issues that need to be considered.

5.1 SHAPE OF THE FORCE-EXTENSION CURVE

In principle, since the formation of a crack will result in a redistribution of load, failure could be detected from a change in the shape of the measured force-extension curve at the point of crack initiation. The slope of the loading curve should decrease as a crack forms because the load bearing area of the bond is reduced. However, where the joint stiffness reduces as load is applied, for example as a toughened adhesive yields plastically, it is difficult to distinguish any effects due to crack formation. In other tests such as the three-point bend, the initiation of fracture seems to be readily apparent, Figure 16.

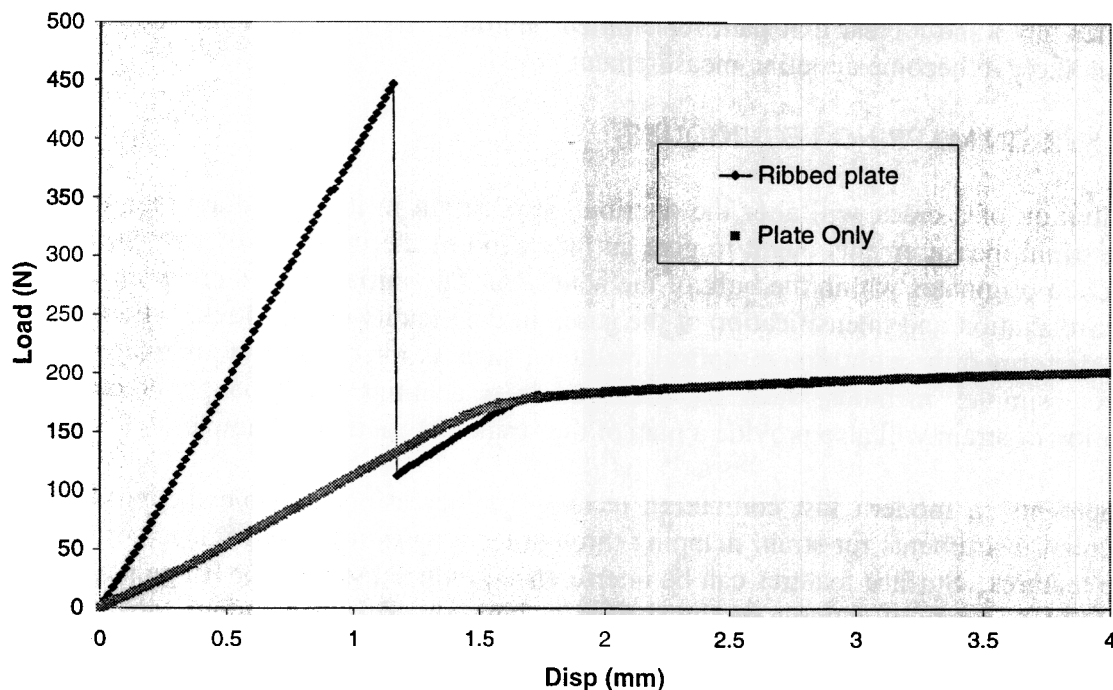


Figure 16: Force-extension curve from 3-point bend adhesion test, point of failure is well defined

5.2 VISUAL INSPECTION

Cracks should to be visible in the adhesive layer. Thus by viewing the edge of the bond it should be possible to see a crack form and grow [44, 45]. High magnification of the region of the joint where failure is expected would be required to view crack formation. Photography or video techniques could be used to record the formation and growth of the crack. There are difficulties with visual detection of cracks. Heterogeneity and surface structures at the joint edge can mask the presence of a crack until it has grown sufficiently. Unless high-speed photography facilities are available, tests need to be performed at slow strain rates in order to capture the crack growth meaningfully.

5.3 EMISSION OF FRACTURE ENERGY

The fracture of an elastic material or bond is accompanied by a release of energy. A portion of this energy will be sound energy. Thus, fracture can be heard. A loud crack can be heard as a brittle adhesive bond fails due to the large amount of acoustic energy emitted by the fast propagating crack. The sound emitted by the initiation of a slow propagating crack in a tougher adhesive will be less and may be difficult to detect aurally above any background noise. Sensitive acoustic transducers placed near the bond line can be used to detect sound from a crack forming and propagating. Analysis of the acoustic signal may yield additional information on the crack location and growth rate. Acoustic emission analysis is a technique being applied to many systems (e.g. composites, coatings) as a research and structural monitoring tool.

The release of electromagnetic radiation may also occur on fracture of a material or interface [113]. Photon emission measurements may provide evidence of the occurrence of failure. However, measurement techniques rely on accurate placement of the detection device (photo multiplier tube) and a clear exit path for emitted photons. This technique is not widely used and is unlikely to become a routine measurement.

5.4 STRAIN MAPPING TECHNIQUES

The initiation of a crack will alter the distribution of strain in its immediate vicinity. Local surface strain measurements ought to give an indication of the initiation of a fracture, even if the fracture originates within the bulk of the adhesive. The initiation of a crack may be detected through relaxation and intensification of the strain in the vicinity of the crack. Strain mapping can be performed through remote optical methods, such as interferometry or image analysis. However, simpler methods, such as strain-sensitive coatings that change colour on the application of strain will also provide a map of the strain distribution in samples.

Developments in modern fast computing technology increasingly enable the production of commercial instruments for strain mapping through techniques involving image correlation of surface features. Surface features can be interference produced speckle or fringe patterns (e.g. Moiré [114]) or natural patterns on the surface of interest. This may reduce the accuracy of strain maps in small regions of critical stress but the initiation of a crack should have sufficient effects on the strain map to be readily apparent.

Internal strains can be characterised through Raman microscopy. Stretching a molecular bond alters its characteristic vibrational properties. With a suitable calibration curve, Raman spectroscopy can be used to determine strains in local regions [85]. X-ray diffraction can

characterise strain in metal adherends close to the adhesive interface. These strains can be used to calculate stress in the adherend close the interface and, by inference, provide information on the interface [115]. Photoelasticity measurements can also be applied where one of the adherends is transparent [116].

6. FINITE ELEMENT APPROACHES FOR INTERFACES

6.1 MODELLING OF AN ADHESIVE INTERFACE

The behaviour of bonded adhesives has been modelled through different approaches using finite element (FE) analysis. In many cases, the adhesive and adherends are modelled using continuum elements, assuming the adhesive is perfectly bonded to the adherends [117-125]. For example Cotton *et al.* [126] determined the interfacial shear strength of a system by assuming the two components were perfectly bonded and that the substrate maintained contact without any slippage. The assumption of a perfect bond means that the finite element analysis takes no account of the adhesion properties of the interface.

There does not appear to be an obvious way of predicting interface strength, as often the input data needed requires knowledge of the interface strength, or the failure stress/strain of the adhesive. But there are ways of accounting for adhesion in an FE analysis, by modelling the way in which the adhesive fails. This section highlights some of the options available. There are two main approaches for modelling the failure of an adhesive interface. One approach is to model the growth of a crack (fracture mechanics energy based approach). A second method is to model adhesive de-bonding (stress or strain based approach).

6.2 FRACTURE APPROACH

In the fracture mechanics approach, a sharp crack is assumed to exist within the material and failure occurs through propagation of this crack. In an adhesive joint, de-bonding may initiate in regions of stress concentration, then grow and cause joint failure. A de-bonded area can therefore be classed as a crack. This approach does not predict the crack initiation stress or energy. The general approach is to relate the crack growth rate (da/dt) through the joint to the applied strain energy release rate, G , or the stress intensity factor, K . Within the literature, authors have considered measured and/or predicted values of G [108, 127, 128] and K [129, 130]. Calculation of the energy release rate, G , is based on linear elastic fracture mechanics (LEFM). This is valid when the plastic zone around the crack tip is very small. LEFM is not necessarily always applicable to adhesives. Toughened adhesives are relatively ductile and therefore do not always exhibit a sharp crack. For non-linear situations, G is replaced by J , the non-linear energy release rate [108, 130, 131]. J is applicable to any stress-strain relationship and is equal to G when the material is linear elastic. J can be written as a path-independent contour line integral giving rise to the name, the J-integral. The J-integral takes account of plastic zone size and is therefore more appropriate than G when the plastic zone size is large. The determination of G for linear elastic materials is relatively straightforward, while determination of the J-integral for non-linear materials is more complex. With FE methods, stresses, strains and displacements along a path can be calculated using the J-integral [108, 130]. As the J-integral is path-independent it can be calculated away from the crack tip and is therefore less affected by approximations in modelling stress and strain fields at the crack tip.

Crack propagation can be simulated by advancing the crack front when the local energy release rate exceeds its critical value. To apply such methods, an initial flaw must be introduced. In

ABAQUS [132] crack propagation can only be modelled along a predetermined surface. Potential crack surfaces must be modelled using contact surface definitions. Surfaces may be partially bonded initially and then may de-bond during crack propagation. The three de-bonding criteria are: crack opening displacement; critical stress criterion at a critical distance ahead of the crack tip; crack length as a function of time. After de-bonding, the interface behaviour reverts to standard contact, including any frictional effects.

Guild *et al.* [133] used the virtual crack growth method, also known as the crack closure method, to model crack propagation. Cracks were introduced into the mesh by renumbering nodes of adjacent elements. Crack tip elements were not used, as point values of stress at the crack tip are not meaningful. The preferred direction of crack growth due to mode I opening could be deduced from examination of the vectors of maximum principal stress. The virtual crack growth method for assessing energy release rate is based on the concept that the energy released in growing the crack is equal to the energy which would be required to close the crack. Forces and displacements at the crack tip are found from FE simulations and calculations of energy can be made subsequently. The shape of the growing crack can be used as a further indication of the likely direction of further crack growth.

6.3 STRENGTH OF MATERIALS APPROACHES

Interface elements can also be used to predict crack growth. In the work of Chen *et al.* [134] interface elements were used via a user subroutine in ABAQUS and were embedded directly in LUSAS. Interface elements were located along the de-bonding interface. This method is based on the indirect use of fracture mechanics in which a softened decohesion material model is provided with traction/relative displacement relationships that are constructed so that the enclosed area is equated to the critical fracture energy. Initial flaws are not required, with initiation being governed by a strength criterion. Two material properties were required for interface elements: G_c , the total energy from experiments and S_t , the assumed interfacial material strength. Both a linear and a cubic decohesion material model were used. In the linear model there is a triangular relationship between traction and the relative displacement (see Figure 17). The triangular area is the critical interlaminar fracture energy, G_c . The stress/strain relationship is defined by the interfacial tensile strength, σ_t , the cracking strain ϵ_0 , and the maximum strain, ϵ_c . In the FE simulation, the strain can exceed ϵ_c but the equivalent stress is zero and the interface is de-bonded. The elements where softening takes place are in the region $\epsilon_0 < \epsilon < \epsilon_c$. The cubic relationship for the decohesion model is shown in Figure 18.

Another method of analysing failure of an interface is using a cohesive zone model. Cohesive zone models have been employed in the study of fracture in many ways, e.g. as phenomenological element breaking rules for fracture, and as models for the process zone ahead of a crack tip. Jagota *et al.* [135] describe cohesive zone models for polymer interfacial fracture that have been implemented as cohesive elements for use with FE codes. The authors suggest that when incorporated between element edges (or faces in 3D) cohesive elements extend conventional FE in a way that allows independent specification of interfacial fracture and bulk constitutive behaviour. The cohesive elements describe the deformation and failure of the interface between two bulk finite elements by specifying the tractions that resist relative motion. The cohesive zone model was implemented in ABAQUS for this work. Bennison *et al.* [136] used the cohesive zone model with FEA to analyse a compression shear strength test to determine adhesion. Cohesive elements were placed along the interface to capture intrinsic and near crack dissipation associated with interface de-bonding. The cohesive elements define the tractions acting across this interface in terms of opening and sliding displacements. The

authors concluded that analysis of the compression shear strength test shows that cohesive elements can be used to treat adhesion/fracture problems where large inelastic deformations characterise the polymer response to loading.

Liechti and Wu [137] used the cohesive zone modelling approach to model rubber/metal de-bonding. They found failing ligaments clearly provided some bridging between crack faces. The failing material in this study was represented by non-linear Kelvin units (non-linear springs and dashpots in parallel). The rate-dependent cohesive force was expressed as the sum of the non-dissipative force (springs) and the dissipative force (dashpot). At a particular ligament extension damage starts to occur at the interface and the stiffness of the interface decreases. At a critical extension, the ligament breaks and the cohesive force vanishes. In the FE model part of the bond line was not connected to the substrate to account for the initial crack length and traction-free boundary conditions. The remainder of the bond line was replaced with an array of equally spaced non-linear Kelvin units to enable crack growth to occur along the interface. Calibration of the cohesive zone model was accomplished via numerical simulations of the observed de-bonding experiments. The values of the parameters of the cohesive zone model were chosen such that the solution for the crack extension history corresponded to the measured de-bonding history at one loading rate.

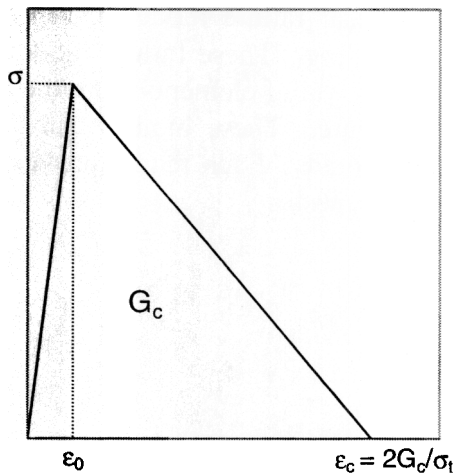


Figure 17. Linear decohesion model

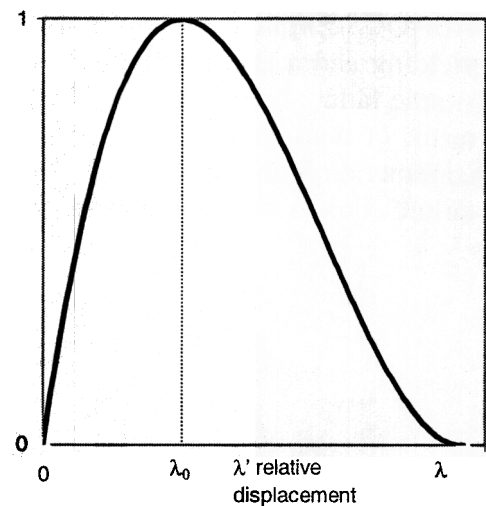


Figure 18. Cubic decohesion model

Coupling elements have also been used to study adhesion. Sebastian [138] modelled FRP plates de-bonding from concrete beams. A non-linear FE analysis used a layered bending-membrane hybrid element for the beam and the plate, along with a coupling element for the adhesive connection. The coupling element was programmed to rupture and to disallow further interaction between the hybrid elements on either side once a predetermined stress level corresponding to the shear bond strength of the plate to concrete connection had been activated. The program has the ability to incorporate non-linear constitutive models for the materials present. The author suggests that the FE program can be improved: the analysis used was a stress-based failure criterion for connection failure, but the author suggests that a fracture mechanics based criterion may be more appropriate.

An alternative de-bonding method can be employed in ABAQUS using the *de-bond option to specify that de-bonding is to be considered. An amplitude-time function (see Figure 19) is used to give the relative magnitude of force to be transmitted between the surfaces at time $t_0 + t_i$ (t_0 being the time when de-bonding begins). When the fracture criterion is met at a node, the force at that node is ramped down according to the de-bonding data (Figure 19). The force at the node must have a value of 1.0 at zero time and must end with a magnitude of zero at the final time i.e. node de-bonded.

Damage modelling is another method for modelling failure of an adhesive. Feih *et al.* [139] modelled a bending test. The adhesive was modelled with isotropic elasticity and von Mises plasticity. Failure of the adhesive was assumed to occur when the maximum tensile plastic strain was reached under tension. Cracking onset of the adhesive was modelled by reducing the transferable stress to 10%. This simplified damage method simulates the stress redistribution inside the adhesive and was employed as a UMAT within ABAQUS. Stabilised integration point degradation was used to degrade the element properties at the integration point once failure was recorded at that point (one element might have different properties at its integration points over a certain period of time). In order to avoid numerical problems due to a singular stiffness matrix, full degradation is modelled using a very small degradation factor of 0.01 rather than zero.

ABAQUS/Explicit also offers two damage models; a shear failure model driven by plastic yielding and a tensile failure model driven by tensile loading. These failure models provide simple failure criteria that are designed to allow stable removal of elements from the mesh as a result of tearing, ripping or tensile spalling of the structure. These models can be used in conjunction with the Mises or Johnson-Cook plasticity models. Each model provides several failure choices including the removal of elements from the mesh.

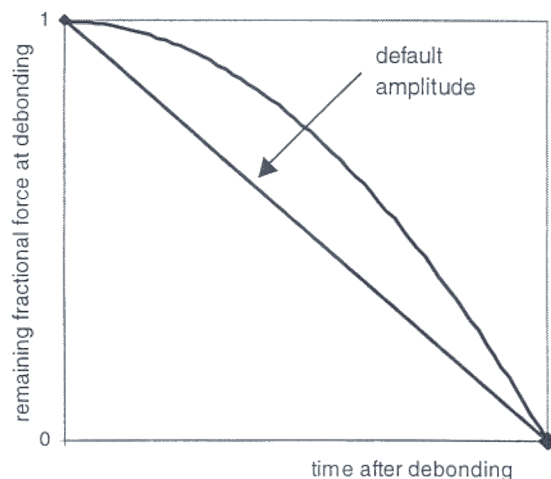


Figure 19. Amplitude-time function used to give the relative magnitude of force to be transmitted

In ABAQUS it is also possible to define breakable bonds that connect the surface of contact pairs from two contact surfaces. Either a time to failure or a damage failure model is used to simulate the post failure response of the bonds. These breakable bonds are design for modelling spot-welds and a spot weld failure criterion is used to model failure. This is a function of the force required to cause failure in tension (mode I loading) and force required to cause failure in pure shear (mode II loading). This method could possibly be used to model de-

bonding of the adhesive/adherend interface. Other possibilities for modelling the adhesive interface include using non-linear spring elements to connect the adhesive elements to the adherend elements, or including a narrow row of elements at the adherend/adhesive interface, with different properties to the bulk adhesive to simulate the interface. This would probably require a very refined mesh of elements and knowledge of how the interface should behave. It might also be possible to use contact surfaces with softened behaviour i.e. as the surfaces move apart the contact pressure between them decreases until it reaches zero (separation).

7. CONCLUDING REMARKS

Potential measurement methods for characterising and quantifying the interfacial adhesion strength properties that are key to the strength of materials systems have been discussed in this review. Some of the approaches that have been taken to include the properties of the interface in design calculations are outlined. There is, at present, no consensus as to best practice in considering the interface in a design. Industry tends to assume a perfect interface when designing adhesive bonds. This is due to both the complexity of models needed to include the interface and the lack of reliable data.

Tests for adhesive joints, fracture toughness and engineering coatings that can provide information on the interface strength have been described. Although there is a plethora of methods available, few of them are capable of providing quantitative data that are readily usable in design calculations. Problems exist in defining the state of stress, strain or fracture energy close to the interface due to the complex stress distributions that are difficult to model accurately (particularly when material responses are non-linear) and the possibility of material properties close to the interface being different to those of the bulk material. In the main, coatings tests are qualitative rather than quantitative. The bend adhesion tests may offer a means of discriminating surfaces for bonding.

There are few joint tests that are applicable to both thick and thin adherends. Obviously, thick adherends can be machined to the dimensions required for tests but this increases the cost of testing. The results from lap joint tests are difficult to interpret owing to the complex distribution of peel and shear stresses near the end of the overlap. Joints with higher stiffness (due to thicker adherends) such as the thick adherend shear, double lap or strap joint ought to give more reliable results. The tapered strap joint offers the possibility of inducing failure at either the thick, central adherend or the thin, straps depending on the joint geometries chosen. This could enable the evaluation of both thin and thick section bonds using the same test configuration.

Peel tests can provide information on bond strengths but these are difficult to relate to a general design situation as converting load per unit width to stress requires making assumptions about the size of the peeling zone. Often fracture in peel tests occurs in the adhesive layer rather than at the interface. Fracture toughness tests offer the capability of characterising the interface. The wedge test is simple and cheap to perform but, whilst well suited for comparing the durability performance of different surface treatments, does not provide accurate data on surface fracture energies. The double-cantilevered beam tests (DCB and TDCB) provide more accurate data. A possible limitation is that fracture may run into the adhesive rather than along the interface.

The pull-off and the pull-out tests maximise stresses at the interface between the adhesive and substrate. Stress distributions are complex but analysis techniques have been developed.

The conditions causing initiation of failure are critical in the interpretation of test results and for the safe design of bonded structures. Techniques for detecting the start of a fracture need to be utilised when testing the material systems in order to maximise the usefulness of the data obtained.

ACKNOWLEDGEMENTS

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