FRACTURE MECHANISMS IN THE PEELING FAILURE OF ADHESIVE JOINTS

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ABSTRACT

The principles of fracture mechanics have been applied to the peel test. The finite element method has been used to investigate the adhesive stresses at the bond end. These stresses have been found to be singular. In the case of the cracked system the relative amounts of modes I and II loading, present at the crack tip, have been determined. These have been found to be essentially independent of the peel loads and angles considered and indicate that the effects of mode II loading cannot be neglected. In the non cracked system the principal stresses have been shown to play a dominant role.

KEYWORDS

Adhesive fracture mechanics; large displacement; peel test; mixed mode; finite element; stress singularity.

INTRODUCTION

Outline of the peel test. This test is a method of assessing the performance of an adhesive under a particular type of loading. The many forms of the test are variations of a common system which is shown schematically in Fig. 1. It has been difficult, however, to correlate the results of such tests with the properties of the adhesive, largely owing to the lack of information about the adhesive stress distribution in the peel test.

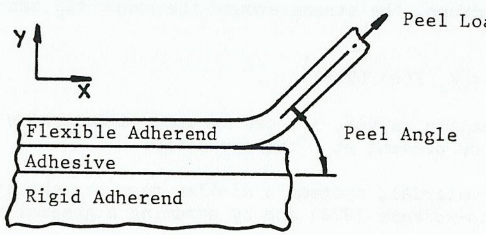

Fig. 1 A schematic representation of the peel test.

Synopsis of existing analyses. Previously the peel test has been represented either by a non-cracked, bi-material model or a cracked single material model. Among the workers who adopt the first approach are Kaelble (1960), who assumes small bending in the attached region, and Nicholson (1977) who considers the effect of large bending. They have modelled the adhesive as a layer of tension and shear springs and assume failure at a maximum stress. Elliott (1973) commented on the importance of considering the cracked adhesive when he proposed the evaluation of an adhesive notch strength.

Bikerman (1961) adopted the second approach, determining propagation by applying an energy balance to the system. This method has been used and extended by several workers (Anderson and co-workers, 1976; Gent and Hamed, 1975 and Kendall, 1973) to attempt to quantify peel failure. These analyses cannot consider mixed mode fracture and are only a simplified model of the real bi-material test.

APPLICATION OF FRACTURE MECHANICS TO THE PEEL TEST

Existing approaches. In applying fracture mechanics principles to bi-material systems, some workers have followed the traditional approach, considering cohesive fracture of the adhesive. Gledhill and Kinloch (1978) have applied linear elastic fracture mechanics to bulk samples of adhesives and adhesive joints. However, based on the principle that cohesive and interfacial fracture are similar in a continuum sense, other workers (Burton and co-workers, 1971, and Anderson and co-workers, 1973) have analysed interfacial fracture of bi-material systems employing existing fracture mechanics principles, using an interfacial fracture energy (γ_i) term in place of the usual cohesive fracture energy (γ) term. Although the interfacial fracture energy is not strictly a material property, in a continuum sense it can be considered as a parameter defining the amount of energy required to break interfacial bonds.

Details of the interfacial approach. In the bi-material peel test the locus of failure is either interfacial between the adhesive and the flexible adherend or cohesive in the adhesive extremely close to the flexible adherend. Thus the interfacial approach, discussed above, will be applied, assuming that the crack will propagate when the energy release rate (G) of the system reaches the interfacial crack resistance (R_i). R_i is assumed to be a function of the mode I and mode II interfacial fracture energies (γ_{iI}, γ_{iII}). The contribution of each being determined by the amount of the respective loading mode present.

As Anderson (1976) found that γ_{iII} could be more than twice γ_{iI} , it is clearly important to determine the amounts of modes I and II present, to enable successful application of the energy principles outlined above.

In cohesive fracture, the stress around the crack tip can be written as (Paris and Sih, 1963)

$$\sigma_i = K_i\ F(\theta)/(2\pi r)^{\frac{1}{2}} \quad .$$

The stress intensity factor, K_i, can be used to determine the relative amount of each loading mode present at the crack tip.

In cracked, bi-material, systems a similar form for the stresses is found (Anderson and co-workers 1973) and by assuming a general relationship for the stresses of

$$\sigma_i = C_i\ r^{-\frac{1}{2}} \quad ,$$

the intensity, C_i, can be used to determine the amounts of the i^{th} mode present at the crack tip.

Two general comments on this approach should be made. First, the effects of plasticity will not be included initially. However in practice the interfacial fracture energy terms include some of these effects and careful choice of adherend and adhesive minimise any remaining errors. Second, this approach is equally applicable if fracture is cohesive, the values of cohesive fracture energy of the adhesive (γ) replacing the interfacial fracture energy (γ_i)

THE FINITE ELEMENT PROCEDURE

The finite element technique in fracture mechanics. This technique has been used many times in uncracked bi-material systems. Chan and co-workers (1970) and Hellen (1975) are among those who have extended the technique to apply the principles of fracture mechanics to cohesive systems. Trantina (1972), and Wang (1976) have used the finite element analysis to investigate cohesive fracture of an adhesive layer in a bi-material system, while Anderson and co-workers (1973) and Lin and co-workers (1976) considered interfacial fracture of a bi-material system. Henshell and Shaw (1975) have produced the characteristic $r^{-1/2}$ singularity of a cracked system by distorting the four elements adjacent to the crack tip and have applied this block successfully to existing fracture mechanics problems. In the present work, the cracked peel test is modelled as interfacial fracture in a bi-material system and the finite element technique is used to obtain the stress distributions around the crack tip and hence the intensities C_1 and C_2 introduced earlier.

The finite element technique and large displacement theory. Not only is the peel test a cracked bi-material system but it does not fulfil the conditions of small displacement theory on which most finite element codes are based. The small displacement theory, which provides the familiar, linear, strain-displacement equations is essentially only true when the rotation of the structure is small; these conditions are not met in any slender body subject to bending e.g. the peel test. If in such a system the displacements are large but the strains are small, then the strain is a non-linear function of the displacement (Martin, 1966) defined as

$$2\varepsilon_{pq} = \frac{\partial D_p}{\partial q} + \frac{\partial D_q}{\partial p} + \left[\frac{\partial D}{\partial p} \cdot \frac{\partial D}{\partial q}\right] \quad p,q = x,y,z$$

$$\underline{D} = u\underline{i} + v\underline{j} + w\underline{k} \text{ (the displacement vector)}$$

Thus, although the problem is non-linear, the material behaviour is still assumed to be linear.

The form of the finite element technique used is the displacement method. The internal and external forces are equated and solved for the unknown displacements. (The internal forces are a function of both the unknown displacements and the stiffness matrix, and the external forces are the applied loads.) In the large displacement analysis, unlike those involving small displacements, the stiffness matrix is a function of the displacements and so the solution has to be approached iteratively, calculating the stiffness matrix, solving for the displacements and, if convergence is not achieved, repeating the procedure. A detailed description of large displacement finite element formulation is given by Nayak (1971).

Other aspects of the finite element technique. A large displacement finite element program, outlined above, was written incorporating both triangular and quadrilateral quadratic isoparametric elements. The quadrilateral elements have been recommended by many workers (Anderson, 1977; Hellen, 1975), and have been used previously with success by the authors. The long thin geometry of the peel test necessitates local mesh refinement in the region of interest. The method of local mesh refinement is illustrated in Fig. 2 and uses triangular elements. Forming a triangular element by collapsing 3 nodes of a quadrilateral element has been found by the authors to introduce errors of more than 30% and it was necessary to use the triangular isoparametric element to remove this error. Henshell and Shaw's crack tip block has been included in the local refinement at the tip of the cracked configuration, Fig. 2. An automatic mesh generating routine has been written incorporationg the previous two features.

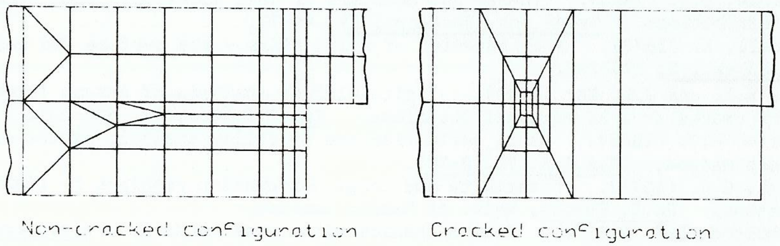

Fig. 2 Details of meshes used in the analysis of the peel test.

RESULTS

The peel test configuration, outlined in Fig. 1, has been modelled as a cracked and a non-cracked bi-material system. Where the system contains a crack it is modelled by giving the adhesive and adherend separate nodes on the interface. The rigid adherend is represented by constraining the appropriate adhesive nodes in both directions. Specific details of the configuration analysed are given below:

Adherend tensile modulus (non-cracked/cracked) Poisson's ratio	200/210 GNm^{-2}, 0·3
Adhesive tensile modulus and Poisson's ratio	2·8 GNm^{-2}, 0·4
Adherend and adhesive thicknesses	0·2 mm, 0·2 mm
Bond length	30 mm
Peel angles (ω)	90^o, 60^o, 30^o
Peel loads (P)	$1Nmm^{-1}$, $0{\cdot}5Nmm^{-1}$, $0{\cdot}1Nmm^{-1}$

The free length of the adherend was chosen so that the difference between the slope at the end of the adherend (calculated using large bending theory) and the nominal peel angle was no more than 0·05°. This resulted in a maximum length of 220mm ($P = 0{\cdot}1\ Nmm^{-1}$, $\omega = 90^o$) and a minimum length of 30mm ($P = 0{\cdot}5\ Nmm^{-1}$, $\omega = 30^o$).

The finite element meshes were refined locally until satisfactory solutions were obtained. The meshes used for the cracked and non-cracked configurations followed the same pattern, the adhesive and the adherend were modelled by coarse elements (10mm × 0·2mm) for most of the structure converging to the refined meshes shown in Fig. 2. The smallest elements were 0.0125mm x 0.0250mm in the cracked configuration and 0·025mm × 0·025mm in the uncracked system.

Investigation of the non-cracked system. To establish confidence in the stresses from the finite element analysis the adhesive stress distribution in the y direction (Fig. 1) is compared with the analysis of Kaelble (1960) for 90° and 30° peel angles ($P = 0{\cdot}5Nmm^{-1}$). Kaelble assumes a constant stress across the adhesive thickness and hence an averaged finite element y - stress is used for comparison. Fig. 3 shows the close agreement between the two solutions.

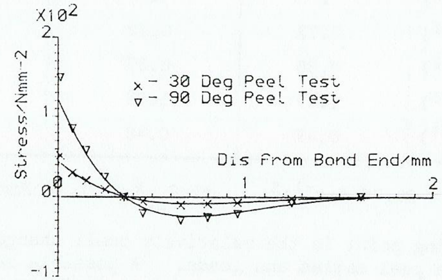

Fig. 3 Adhesive y-stress distribution in the 90° and 30° non-cracked peel test.

The authors believe that initial failure of the peel test may be caused by the maximum stress in the adhesive reaching a critical value. Fig. 4 shows details of the principal stresses in the adhesive, indicating that the maximum stress occurs at the bond end adjacent to the flexible adherend and that when failure occurs the crack will propagate along the interface, as is found in practice. The plot shown is for a 90° peel angle ($P = 0{\cdot}5Nmm^{-1}$) but is characteristic of lower peel angles and other load cases.

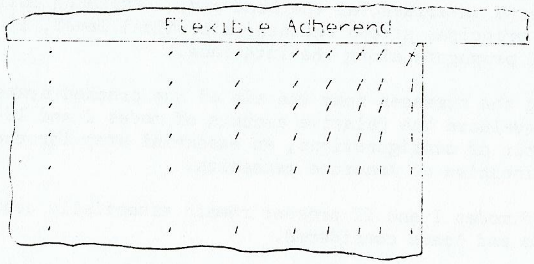

Fig. 4 Adhesive principal stresses in the 90° non-cracked peel test.

Investigation of the cracked system. The main purpose of this section of the analysis was to determine intensity factors (C_i), for the y and shear stresses along the interface and hence the amounts of modes I and II present at the crack tip. The singular relationships for the stresses, discussed earlier:

$$\sigma_i = C_i\ r^{-1/2}$$

were assumed and the intensity factors, C_i, were calculated. The results obtained for all the configurations are given in Table 1.

Table 1 Adhesive Intensity Factors for the Cracked Peel Test

Configuration	†Intensity I Ratio (C_I/C_I^*)	Intensity II †† Ratio (C_{II}/C_{II}^*)	Mode Ratio (C_I/C_{II})	Moment Ratio (M/M^*)
90° ($P = 0.5$ Nmm^{-1})	1	1	2.41	1
60° ($P = 0.5$ Nmm^{-1})	0.72	0.73	2.39	0.71
30° ($P = 0.5$ Nmm^{-1})	0.36	0.37	2.36	0.37
90° ($P = 1.0$ Nmm^{-1})	1.37	1.35	2.45	1.41
90° ($P = 0.1$ Nmm^{-1})	0.47	0.48	2.37	0.45

† $C_I^* = 26.77$ Nmm$^{-1.5}$ †† $C_{II}^* = 11.10$ Nmm$^{-1.5}$

The most interesting point is the relatively small change in mode ratio over a wide range of both peel angles and loads. A possible reason for this is that adherend bending and not direct tension mainly influences the adhesive stresses, demonstrated by showing that the intensities are essentially proportional to the applied bending moment (Table 1). Initial indications are, then, that the amount of modes I and II present at the crack tip can only be dependent on the material properties and thicknesses used in the peel test.

The ratios of modes I and II present indicate that the effects of mode II loading will be significant and cannot be neglected.

CONCLUSIONS

A large displacement finite element analysis of the peel joint has been made. Both cracked and non-cracked systems have been investigated. In the non-cracked system it has been shown that the maximum principal stress occurs at the adhesive-flexible adherend interface, at the bond end. Assuming initial failure to be caused by the principal stress reaching a critical level, it has been shown that the crack will propagate along the interface.

By considering the stresses near the tip of the cracked system, the authors have been able to evaluate the relative amounts of modes I and II present at the crack tip for a number of configurations, an essential step for the successful use of the energy principles of fracture mechanics.

The amounts of modes I and II present remain essentially constant over the range of peel angles and loads considered.

The effects of mode II loading cannot be neglected, a simplification often made in the analysis of the peel test.

REFERENCES

Anderson, G.P., K.L. Devries and M.L. Williams (1973). Finite element in adhesion analysis. Int.J.Fract., 9, 421-435.
Anderson, G.P., K.L. Devries and M.L. Williams (1976). The peel test in experimental adhesive-fracture mechanics. Exp.Mech., 24, 11-15.
Anderson, G.P., S.J. Bennett and K.L. Devries (1977). Analytical methods and computer techniques for adhesive bonding. In G.P. Anderson (Ed.), Analysis and testing of adhesive bonds, Academic Press, New York, 121-153.

Bikerman, J.J., (1961). Stresses in adhints. In J.J. Bikerman (Ed.), The Science of Adhesive Joints, Academic Press, New York, 190-192.
Burton, J.D. and W.B. Jones (1971). Theoretical and experimental treatment of fracture in an adhesive interlayer. Trans.Soc.Rheology, 15, 39-50.
Chan, S.K., I.S. Tuba and W.K. Wilson (1970). On the finite element method in linear fracture mechanics. Eng.Frac.Mech, 2, 1-17.
Elliott, S.Y., (1973). Techniques for the evaluation of adhesives. In C.V. Cagle (Ed.), Handbook of Adhesive Bonding, McGraw-Hill, 32-1, 32-26.
Gent, A.N. and G.R. Hamed (1975). Peel mechanics. J.Adhes., 7, 91-95.
Gledhill, R.A. and A.J. Kinloch (1978). Relationship between mechanical properties and crack propagation in epoxy resin adhesives. Polymer, 19, 574-582.
Hellen, T.K. (1975). On the method of virtual crack extensions. Int.J.Num. Methods Eng., 9, 187-207.
Henshell, R.D. and Shaw, K.G. (1975). Crack tip finite elements are unnecessary. Int. J. Num. Methods in Eng. 9, 495-507.
Kaelble, D.H. (1960). Theory and analysis of peel adhesion: bond stresses and distributions. Trans.Soc. Rheology, IV, 45-73.
Kendall, K. (1973). Peel adhesion of solid films - the surface and bulk effects. J.Adhes., 5, 179-202.
Lin, K.Y. and J.W. Mar (1976). Finite element analysis of stress intensity factors for cracks at a bi-material interface. Int.J.Fract., 12, 521-531.
Martin, H.C. (1966). Large deflection and stability analysis by the direct stiffness method. N.A.S.A. TR 32-931.
Nayak, G.C. (1971). Plasticity and large deformation problems by finite element method. Ph.D. Thesis, Univ. of Wales, Swansea.
Nicholson, D.W. (1977). Peel mechanics with large bending. Int.J.Fract., 3, 279-287.
Paris, P.C. and G.C. Sih (1965) Stress analysis of cracks. ASTM.STP 381, 30, 81.
Trantina, G.G. (1972). Fracture mechanics approach to adhesive joints. J.Comp. Matls., 6, 192-207.
Wang, S.S., J.F. Mandell and F.J. Mcgarry (1976). Fracture of adhesive joints. Research report R 76-1., Massachusetts Inst. of Tech.