IOM Adhesives Section

Stress Analysis and Fracture in Adhesive Joints

April 18th 1996

The Institute of Materials Adhesives Section has the following committee members

Prof R D Adams	Chairman
Mr J A Bishopp	Vice-Chairman
Mr M R Bowditch	Secretary
Prof J Comyn	Publicity Officer
Dr K W Allen	Treasurer
Mr S G Abbott	
Dr D G Dixon	
Mr A Haward	
Dr T B Jones	
Prof A J Kinloch	
Dr G J Lake	
Mr J D Palmer	
D A Tod	

The next major event being organised by the Adhesives Section is the third European Conference on Adhesion, Adhesion 96/Euradh 96. This will be held in Cambridge 3-6 September 1996.

The next one day meeting will be held on thursday 12th December 1996. This will be the meeting "Curing of Adhesives" originally schedule for 18th April.

Details of both events can be obtained by contacting

David Tod
DRA
WX4/X50
Fort Halstead
Sevenoaks
Kent TN14 7BP
01959 514492
01959 516014 (fax)

Programme

10.30	Coffee and Registration
11.00	AN OVERVIEW ON STRESS AND STRENGTH ANALYSIS FOR BONDED JOINTS R D Adams (University of Bristol)
11.30	SOME STUDIES OF FAILURE CRITERIA FOR ADHESIVE JOINTS J McCarthy (AEA Technology)
12.00	APPLICATION OF FRACTURE MECHANICS TO JOINT FAILURE FOR RUBBERY MATERIALS G J Lake (MRPRA)
12.30	DEFECT TOLERANCE OF BONDED CONNECTIONS IN GRE PIPES M J Cowling, S Lafferty and S A Hashim (GMTC)
13.00	Lunch
14.30	IMPACT TESTING, DURABILITY AND LIFETIME PREDICTION OF ADHESIVE JOINTS A C Taylor, B R K Blackman, A J Curley, A J Kinloch and Y Wang (Imperial College)
15.00	ADHESIVELY BONDED REPAIRS OF FIBRE-COMPOSITE MATERIALS M N Charalambides, A J Kinloch and F L Matthews (Imperial College)
15.30	Tea
15.45	FATIGUE AND FRACTURE ANALYSIS FOR ENVIRONMENTAL LIFE ASSESSMENT OF BONDED STRUCTURES R Martin and J Harris (MERL)
16.15	CREEP AND FATIGUE INTERACTIONS IN ADHESIVE JOINT FAILURE A Crocombe, X X Xu, W Ge and P A Smith (University of Surrey)
16.45	Close

ADAMS R D	UNIV OF BRISTOL
ALLEN K W	SELF
ANSARIFAR M A	TUN ABDUL RAZAK
ARAGON H L	MRPRA
ARIAN B	ALCAN INT
ARMSTRONG K B	SELF
BEEVERS A	OXFORD BROOKES
BLACKMAN B R K	IMPERIAL
BOWDITCH M	DRA
CHAPMAN A V	MRPRA
CHARAMLAMBIDES M N	IMPERIAL
CLARKE A	UNIV OF BRISTOL
COMYN J	LOUGHBOROUGH UNIVERSITY
COWLING M J	GLASGOW MARINE
DAVIES R G H	UNIV OF BRISTOL
DIXON D G	BRITISH AEROSPACE
DURODOLA J F	OXFORD BROOKES
FENG X	IMPERIAL
FRASER S	UNIV OF SHEFFIELD
GUILD F DR	UNIV OF BRISTOL
HASHIM S A	GLASGOW MARINE
HOBMAN C E	DRA
JACKSON R S	IMPERIAL
KINLOCH A	IMPERIAL COLLEGE
LAKE G J	MRPRA
LITTLE M S G	IMPERIAL
MATTHEWS F L	IMPERIAL COLLEGE
MUNDY J S	BUILDING RESEARCH
POTTER K D	UNIV OF BRISTOL
RAGG J S	NORTEL
SARGENT J	BRITISH AEROSPACE
TAYLOR A C	IMPERIAL
THARME C	UNIV OF BRISTOL
THOMAS G	TWI
THOMAS R	UNIV OF BRISTOL
TOD D A	DRA
TOWSE A	UNIV OF BRISTOL
VAN STRAALEN I J	TNO
VAUGHN L	UNIV OF BRISTOL
WANG G	SURREY UNIV
WIBBERLEY B L	UNIV OF HERTS
WILLIAMSON J R	AWE PLC
WISNOM M R	UNIV OF BRISTOL
WYLIE P D	DRA
YU H	UNIV OF BRISTOL

An overview on stress and strength analysis for bonded joints

R D Adams

Department of Mechanical Engineering, University of Bristol, Bristol, UK

Our basic aim is to devise methods of predicting the strength of adhesively-bonded joints. We recognise that to do this on a full scientific basis, using a combination of material science and advanced numerical analysis for stress and strain analysis, is only possible in a university or advanced industrial laboratory.

As applied scientists, we see this process as germane to our activity. But as engineers, we also see the need to transfer this knowledge and understanding to industry.

We are therefore in a dilemma. Using the old-fashioned closed-form algebraic analyses based on the classical work of Volkersen[1] and Goland and Reissner[2] involves simplifications so great that reality is lost. But to advocate the blanket use of finite element analysis is equally futile as the learning-curve is long, the cost is high, and, unless great care is used, the results are no more useful than the algebraic methods.

The basic problem is that in all practical joints, a stress concentration exists. At a square or sharp corner (if one exists!) the stress is infinite. Even adhesive plasticity does not help as this only reduces the problem to one of infinite strain. We cannot use fracture mechanics as there is no crack present. To postulate the existence of a crack which allows data-fitting is to debase the problem to one of empiricism. And then what length of crack do you assume for some other adhesive or joint geometry. Is the assumed crack length affected by such uncontrollable variables such as bond-line thickness?

In effect, we have to look at the challenge from several directions. First, we recognise the importance of a powerful finite element analysis. Second, we need reliable data (adhesive properties) to put into that analysis. Third, we need to iterate between the predictions of the analysis and experimental results on real joints in order to prove that the failure predictions work. We need to bring together these three elements in an interdisciplinary approach in order to develop a rational methodology for predicting joint strength.

And how is that to be applied to the design and use of adhesives in industry? First, we need a simplified analysis procedure - but how simple? Second, we need, as before, reliable adhesive properties. Finally, we have to correlate with experiment to prove the validity of the simplified analysis. The secret is the degree of simplification. This can only be satisfactorily determined by studying the results of the scientific investigation. In other words, technology transfer can only be achieved when the fundamental scientific background is fully understood and verified by experimental results. As stated by Sharpe[3], the breaking strength of an adhesive joint is determined by the mechanical properties of the materials used, the geometry, the interfaces, and so on. Fortunately, for the vast majority of well-made structural adhesive joints, failure takes place within the adhesive, which we can characterise, rather than at the interface or in the interphase, the properties of which are difficult to measure.

References

1. Volkersen, *O., Luftfarhtforschung* 15, 41 (1938).

2. Goland, M. and Reissner, *E., J. Appl. Mech.,* Trans. ASME 66, A17 (1944).

3. Sharpe, L.H., *ASM Engineered Materials Handbook,* Vol. 3, 1990, "Overview: Adhesives Technology", pp. 33038

Some Studies of Failure Criteria for Adhesive Joints

John McCarthy
AEA Technology plc

Many UK manufacturers are aware of the merits of adhesives in certain critical roles. However the range of applications of adhesives is still limited largely due to the lack of consistent test methods, validated test data and proven failure criteria, which the engineer needs in order to specify adhesives for a given application. These requirements formed the basis of a series of five projects sponsored by the Department of Trade and Industry under its Mechanical Testing and Standards Programme. The work presented here formed a part of one of the projects entitled 'Failure Modes and Criteria' and carried out through a collaboration of AEA Technology, Surrey University and Imperial College.

The project addressed the issue of failure criteria initially through an extensive study of joint fracture followed by investigation and development of test methods for fracture properties and failure criteria. This paper draws on some of the work from the joint tests and investigations of failure criteria and presents some conclusions from the project. The project ran between 1992 and 1996, lasting just over three years. All technical work is now complete and final reports are being prepared. Copies of technical reports can be obtained from the author of this paper.

Table 1 outlines the joint types, loading regimes and adhesives used in the project.

Load Cases	quasi-static cyclic fatigue creep impact.
Joint Types	TAST (thick adherend shear) T Peel TLS (thin lap shear) TDCB (tapered double cantilever beam) CDCB (contoured double cantilever beam) narrow linear tapered DCB wide linear tapered DCB CLS (cracked lap shear) Block Shear 3 Point Bend Wedge Peel
Adhesives	Ciba Geigy AV119 Permabond F241

Table 1: Joint Types, Load regimes and Adhesives used in the Project.

This technical content of this paper focuses on the quasi-static failure criteria studies and suggests the use of a cohesive and adhesive failure criterion for quasi-static loading that gave good results for the joints studied in the project.

Some Studies of Failure Criteria for Adhesive Joints

Table 2 outlines the types of analysis and failure criteria investigated for quasi-static loading. The aim was to generate analyses which were representative of both those used for design (possibly from closed form solutions giving bond centreline stresses and strains only) and those used for detailed studies.

Quality of Analysis	Type of Criterion
Low Closed form type or finite element analysis with one element through thickness of adhesive. Linear and non-linear using von Mises and pressure dependent yield criteria.	Peak Principal Strain at a Point or over a Distance. Peak Principal Stress at a Point or over a Distance. Peak Peel Stress at a Point or over a Distance. Peak Shear Strain at a Point or over a Distance. Peak Shear Stress at a Point or over a Distance. Equivalent Stress at a Point or over a Distance. Equivalent Plastic Strain at a Point or over a Distance.
Medium Detailed, non-linear finite element analysis using von Mises yield i.e. ~8 elements through the adhesive thickness.	Peak Principal Strain at a Point or over a Distance. Peak Peel Stress at a Point or over a Distance. Peak Shear Strain at a Point or over a Distance. Peak Shear Stress at a Point or over a Distance.
High Detailed, non-linear finite element analysis using pressure dependent yield and adhesive and interfacial failure.	Peak Principal Strain at a Point. Peak Interfacial (Peel) Stress

Table 2: Failure Criteria and Types of Analysis investigated for Quasi-static Loading

Some conclusions from these studies are as follows.

1. Extensive work has been performed by many researchers over the past 40 years to quantify the stress/strain distribution in adhesive joints. Many of these analyses have shown that the strain predicted at certain areas of joints can become theoretically infinite due to strain concentrating effects such as sharp corners. These effects make the application of simple maximum value at a point criteria difficult because the value of strain generated from the analysis and which is compared to the critical value, depends upon the proximity of the point under consideration to the strain concentrator.

2. Criteria which depend upon a critical value occurring over or at a prescribed distance provide a means to over come this problem of infinite strain prediction but there is no apparent physical basis for these criteria. However this type of criterion has been found to produce reasonable predictions of ultimate strength within a joint type and over a limited range of dimensions.

3. The work on existing criteria concluded that there was no evidence that failure criteria based upon stresses or strains over or at a distance work in general i.e. between joint types and for joints of the same type with large variations in geometry. This conclusion is unaffected by the quality of the stress/strain predictions. However a reasonable correlation

was found within joint types and for limited ranges of geometry i.e. a criterion which has been demonstrated for a particular joint type and size may be used to predict the strength of joints of the same type which are of similar dimensions.

4. Toughened adhesives are inherently non-linear. Simple analyses which neglect non-linearity or which fail to quantify joint rotation/material non-linearity cannot give a true picture of the stress/strain within the joint.

5. Adhesives are polymeric materials that exhibit pressure sensitive yield and failure. For instance AV119, a rubber toughened epoxide adhesive will strain to over 50% nominal strain in pure shear but will fail at modest strains of less than 10% in tension. Detailed failure studies need to incorporate these effects.

6. To predict failure across all three joint types considered in the project i.e. TAST, TLS and T Peel, regardless of dimensions, a mixed mode failure criterion is proposed which incorporates interfacial (adhesion) failure at some critical stress and cohesive failure at some peak principal strain within the adhesive.

7. A material model has been implemented in an explicit finite element code (DYNA3D) which accounts for pressure sensitive yield and pressure sensitive failure strain behaviour in a non-linear adhesive material. Using this model in conjunction with interface elements to simulate adhesion failure at the adhesive/adherend interface has generated good predictions of overall joint stiffness with load and reasonable correlation with observed phenomenon. The adhesion failure acts to limit the maximum strains predicted within the joint at the ends of the adhesive overlap and provides a better correlation between adhesive strains at maximum load. Using this combined criteria appears to give reasonable prediction of ultimate failure load and mode across joints of different types and of dimensions

ACKNOWLEDGEMENTS

The following are gratefully acknowledged for their respective contributions.

- The support of and funding from the DTI under the Materials Technology and Standards (MTS) budget.
- The work of the Centre for Adhesive Technology (CAT) in proposing the original project scope.
- The work of numerous staff at AEA Technology, Imperial College and The University of Surrey.
- The discussions with and test results from the MTS Adhesives Project 1 team at NPL, TWI and University of Bristol.

Application of Fracture Mechanics to Joint Failure for Rubbery Materials

G.J. Lake

A fracture mechanics approach based on the rate at which strain energy is released by a growing crack, has proved very helpful in treating cohesive failure in elastomers, both from a fundamental viewpoint and in relation to service problems. A single relation between the strain energy release rate and the rate of crack growth provides a characteristic, geometry-independent property that can be used to characterise cohesive failure under many, though not all, circumstances.

The situation with regard to the failure of adhesive joints is less straightforward. For relatively weak joints, a simple energetics approach can often allow results for different geometries to be interrelated, but even in these cases exceptions sometimes occur. Fur stronger joints, the approach can seldom be applied in a straightforward way. Some of the complexities will be reviewed and possible reasons for them discussed.

Defect Tolerance of Bonded Connections in GRE Pipes

M. J. Cowling, S. Lafferty and S. A Hashim
Glasgow Marine Technology Centre
University of Glasgow
Glasgow, G12 8QQ, UK

Introduction

In recent years the use of composite piping systems in the offshore industry has become more widespread. These systems consist mainly of glass reinforced epoxy matrix pipe designed primarily for containment of internal pressure. The pipes are manufactured in sections and joined in the field, often by the butt and wrap or the adhesively bonded joint. The butt-and-wrap joint requires fabricators skilled in the hand lay-up process which results in high assembly costs, whereas, the adhesively bonded joint can easily be assembled by most pipe fitters on site. Therefore it is likely that adhesively bonded joints will become more universal. As pressure ratings increase the integrity of the adhesively bonded connection becomes increasingly important and could be the limiting factor on the use of high strength pipes.

Whilst inspection of composite materials and the bonded connections between components using base resin or alternative structural adhesives, is inherently difficult, a major limitation is a lack of understanding of the inspection requirement. Until a coherent strategy, for assessing whether a defect of a specific nature and size requires repair for a specific service requirement has been established. The target performance of any inspection process is unknown. This research aims to provide the information to create the strategy required for the assessment of typical defects in such bonded connections.

Joint Configuration and Fabrication Process

The joint under consideration was the taper/taper adhesively bonded connection which joins 3420 series (100mm diameter) Ameron pipe. The bond length was 70mm, pipe wall thickness was 3.5mm and bond line thickness was 0.1mm.

Bonded pipe connections (full-scale and ¼ sections) were fabricated under carefully controlled conditions to avoid excessive experimental variability. This involved surface abrasion, with an abrasive wheel, immediately followed by surface degreasing with acetone. The adhesive open time, cure procedure and test rate were similar for every specimen. The adhesive used initially was Ameron RP48 but this was superseded by XD4416.

Several full scale taper/taper joints were fabricated using RP48 and 4416 adhesives. The experiments using tensile loading, with and without internal pressure, were performed on a displacement controlled Instron machine at a cross-head rate of 0.5mm/min. Strain gauges were placed along the coupling and pipe to capture the strain distributions. Due to the numerous combinations of possible debond position and debond size it was decided to concentrate on debonds which spanned the circumference (axisymmetric) and were extended different amounts in the axial direction.

Finite Element Models

The finite element models were constructed using PATRAN and the analyses were performed using ABAQUS 5.4. A sub-section of the joint was modelled with symmetry constraints applied to simulate the effect of the remainder of the joint. The pipe and coupling were modelled with 10 layers of orthotropic lamina. Five layers of elements are used through the adhesive thickness and a 45° spew fillet was modelled at the edge of the joint each having elasto-plastic properties. Tensile loads were applied using a nominal displacement. Later models had debonds incorporated in a series of locations and a fracture mechanics approach was used to characterise the strength of the defective joints in terms of the critical strain energy release rate.

Results

The finite element model of the taper/taper joint gave excellent failure predictions for the loading conditions considered. The increased strength and ductility of the 4416 adhesive reduced the stress concentrations at the edge of the joint resulting in a 4% increase in joint strength. For a perfect taper/taper 100mm joint bonded with 4416 adhesive, the pipe is the critical region and not the adhesive layer. Addition of 20 Bar design pressure had no effect on the joint strength when compared to tensile loading alone.

Very large defects can be tolerated within the joint without affecting joint strength unduly. The most critical debond position is at the edge of the joint, whereas large debonds in the middle or nose of the joint have no affect on joint strength.

Impact Testing, Durability and Lifetime Prediction of Adhesive Joints.

A.C. Taylor, B.R.K. Blackman, A.J. Curley, A.J. Kinloch, Y. Wang.

Department of Mechanical Engineering, Imperial College of Science, Technology and Medicine, Exhibition Road, London SW7 2BX, UK.

The tapered double-cantilever beam (TDCB) geometry has been used to obtain fracture energy, G_c values for toughened epoxy adhesives at test rates up to 5 m/s. This has shown a decrease in G_c of up to 36% between static and high rate loading. The same adhesives have been tested using the impact wedge peel geometry. A correlation between the wedge cleavage force and the G_c value from the TDCB tests has been indicated. A finite element model has been used to predict the cleavage force from the crack length data for the impact wedge peel test. Cyclic fatigue tests using the TDCB geometry have been performed on one of the adhesives. The data obtained have been used to predict the lifetimes of single lap joints under the same conditions using an analytical and a finite element model.

1. Introduction

The increasing use of adhesives has created a need to evaluate their performance under 'extreme' conditions[1]. This work looks at the effect of high loading rate, cyclic fatigue and water immersion on a range of rubber-toughened epoxy adhesives.

2. Impact

2.1 Fracture Mechanics Tests

High rate tests were performed to obtain values of fracture energy, G_c, for the adhesives as a function of the loading rate. Chromic acid etched (CAE) aluminium alloy adherends were used, see Figure 1. The TDCB specimens were loaded in mode I tension at test rates of up to 5 m/s. The beam displacement and crack length values were recorded via high-speed photography. A high-frequency response piezo-electric load-cell was used to measure the force-time response of the specimen.

The experimental data was analysed to give the G_c values using the common form of the static analysis, Eqn (1). However at high rate, dynamic effects cause the measured force oscillate, and so the 'true' failure load is uncertain. Thus a load independent analysis must be used, Eqn (2).

$$G_c = \frac{4P^2 m}{E_s B^2} \qquad (1)$$

$$G_c = \frac{E_s}{16m} \cdot \left(\frac{\dot{\delta}}{\dot{a}} \right)^2 \qquad (2)$$

where P is the load, m is a specimen geometry constant, E_s is the substrate modulus, B is the beam width, $\dot{\delta}$ is the test velocity, $\dot{a}$ is the mean crack velocity and h is the height of the beam.

The results, see Figure 2, show that all the adhesives suffered a reduction in G_c as the test rate is increased. Reductions of up to 36 % were observed over the range 10^{-5} to 5 m/s.

2.2 Impact Wedge Peel Tests

The impact wedge peel test was introduced as an International Standard[2] in 1993. Grit-blasted and degreased sheet metal adherends, 20 mm wide and 0.9 mm thick were bonded over a length of 30 mm. Aluminium alloy and steel substrates were used, the unbonded arms being pre-formed to give a 'tuning fork' profile. An instrumented wedge was pulled through the bonded portion at a velocity of 2 m/s, as shown in Figure 3. The force-time response of the specimen was recorded.

The average cleavage force was calculated from the force-time data, disregarding the first 25% and the last 10% of the trace. This should only be done for <u>stable</u> failure, see Figure 4, where a peak and a plateau region are seen in the force-time response. For <u>unstable</u> failure, where a peak only is seen, a zero force value should be quoted.

A two-dimensional finite element analysis of the impact wedge peel tests was performed using the ABAQUS commercial FE package. The fracture was simulated by releasing the nodal constraints along the crack path at the crack velocity observed from the high speed photography. The force on the wedge was calculated, and compares well with the measured force-time trace, as shown in Figure 4. A virtual crack closure technique was used to estimate the adhesive fracture energy from the IWP test data. For example, for the 'XB5315' adhesive the experimental fracture energy, (from the TDCB tests) and the FE-predicted value are equal, 1.5 kJ/m^2.

The cleavage force measured experimentally at 2 m/s can be plotted against the adhesive fracture energy, G_c, obtained from the TDCB tests, see Figure 5, and a good correlation between the two is indicated. The use of steel as the adherend material in the IWP test gives a higher cleavage force than with aluminium alloy adherends.

3. Durability

3.1 Tapered Double Cantilever Beams

The effect of an aqueous environment on the durability of the 'AV119' adhesive was investigated using the TDCB geometry. Steel and aluminium substrates were used, prepared with a gritblast and degrease or a chromic-acid etch (aluminium only) surface treatment.

The static mode I fracture energy, G_c, of each adhesive/substrate combination was measured by performing TDCB tests at 10^{-5} m/s, as above. The same specimen geometry was also used to find the relationship between the rate of crack growth and the maximum applied fracture energy, G_{max}, under cyclic loading at 5 Hz. These tests were conducted at 23°C in a 'dry' environment (i.e. 55 % relative humidity), and with the specimen immersed in distilled water at 28°C.

The data indicated a threshold value of G_{max} (denoted by G_{th}) for each adhesive/substrate combination below which crack growth did not occur. The value of this threshold was unique for each combination of adhesive, substrate, surface treatment and environment.

The value of the fatigue threshold, G_{th}, was far lower than the static fracture energy, G_c. For example, the adhesive was found to have a static G_c value of about 700 J/m^2, however in 'dry' fatigue the threshold was 170 J/m^2. Both failures were cohesive in the adhesive. The value of G_{th} was reduced further by water immersion. For example, with the gritblasted and degreased aluminium substrate a G_{th} value in water of only 25 J/m^2 was recorded. Failure occurred through the oxide layer. Thus there is a 95 % reduction between the static value of G_c and the fatigue threshold, G_{th}, for a 'wet' fatigue test, using gritblasted and degreased aluminium-alloy substrates. Generally the chromic-acid etch treatment resulted in the better durability, see Figure 6.

3.2 Lifetime Prediction

The fatigue data from the TDCB tests was used to predict the lifetime of single lap joints. Steel substrates were used, bonded with the 'AV119' adhesive. An analytical[3] and a finite element model were used to describe the variation of G_{max} with crack length in the lap joint. These assume that the joint cracks from both ends of the overlap. The analytical model assumes that failure is controlled by mode I stresses at the ends of the overlap. The predictions were found to be close to the experimental results, especially for low applied stress levels, as shown in Figure 7.

4.0 Conclusions

The high rate TDCB tests showed that the adhesives suffered reductions in G_c of between 10 and 36% between test rates of 10^{-5} and 5 m/s. Oscillations, due to stress wave effects in the beam, were evident in the load measurements. The more reliable values of G_c are obtained from beam theory solutions which are independent of the measured load.

There is a good correlation between the cleavage force from the impact wedge peel tests and the adhesive fracture energy, G_c, from the TDCB tests. A finite element model has shown that the adhesive G_c value measured in the TDCB tests can be estimated successfully from the IWP tests.

'Wet' and 'dry' fatigue tests were conducted using TDCB specimens. All tests showed a threshold value of the fracture energy, G_{th}, below which crack growth does not occur. The value of this threshold depended on the adhesive, substrate, surface treatment and test environment, but was far lower than the static fracture energy, G_c.

Steel lap joints bonded with 'AV119' were tested in 'wet' fatigue. These showed an increasing joint life with decreasing applied stress, and produced evidence of a threshold, below which failure does not occur, at around 30 % of the static stress. Analytical and finite element lifetime prediction models were used to predict the fatigue life of the lap joints from the TDCB fatigue data, and gave good agreement with the experimental results.

Acknowledgements

The authors would like to acknowledge the support of the DTI MTS programme, AEA Technology and the EPSRC.

References

1. Blackman, B.R.K., *et al. Journal of Materials Science*, 30, 5885-5900 (1995).
2. ISO. *ISO 11343* (1993).
3. Kinloch, A.J. & Osiyemi, S.O. *Journal of Adhesion*, 43, 79-90 (1993).

Figures

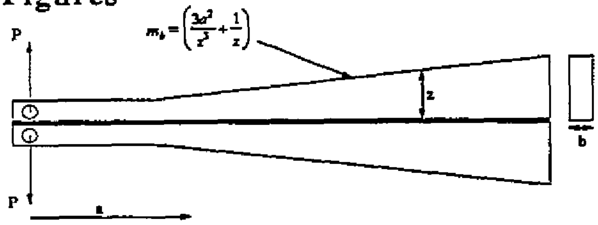

Figure 1: The tapered double cantilever beam (TDCB) test specimen.

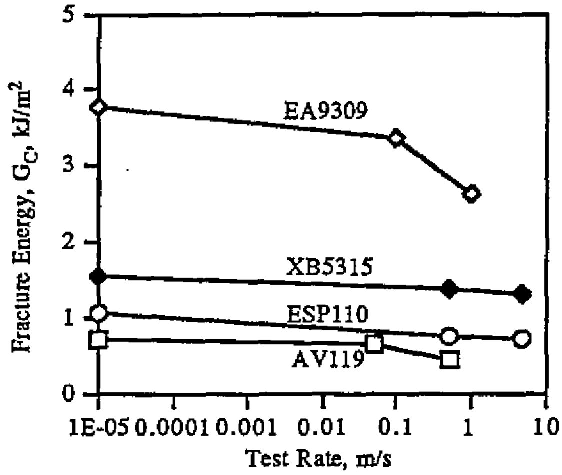

Figure 2: The effect of test rate on adhesive fracture energy, TDCB tests.

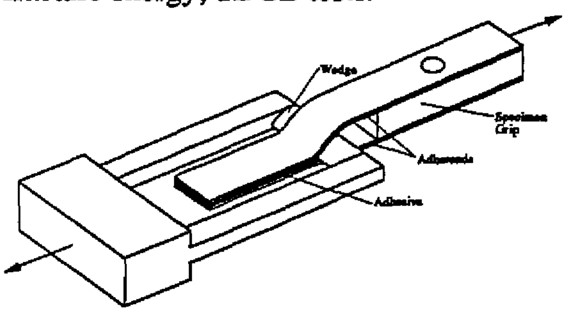

Figure 3: The impact wedge peel (IWP) test.

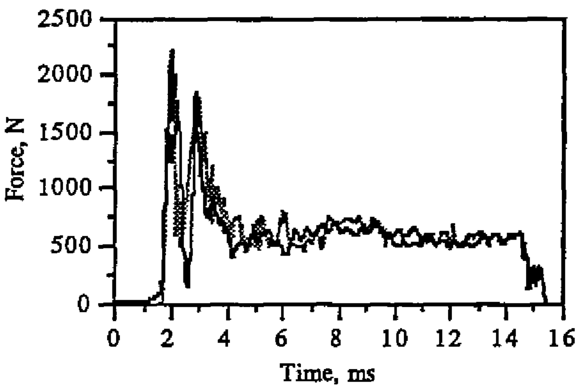

Figure 4: Force versus time trace for steel IWP specimen bonded with XB5315, tested at 2 m/s. Solid line is experimental data, dashed line is FE prediction.

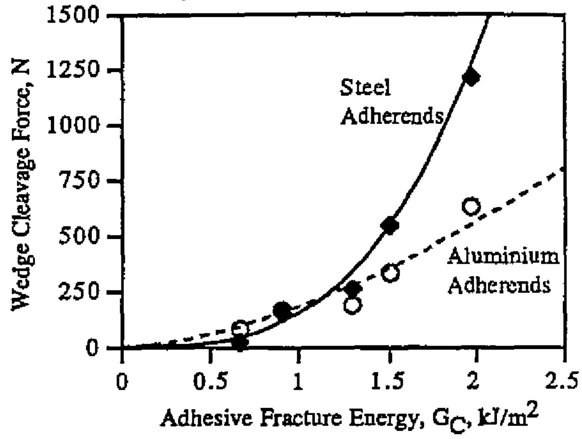

Figure 5: IWP wedge cleavage force versus TDCB fracture energy correlation.

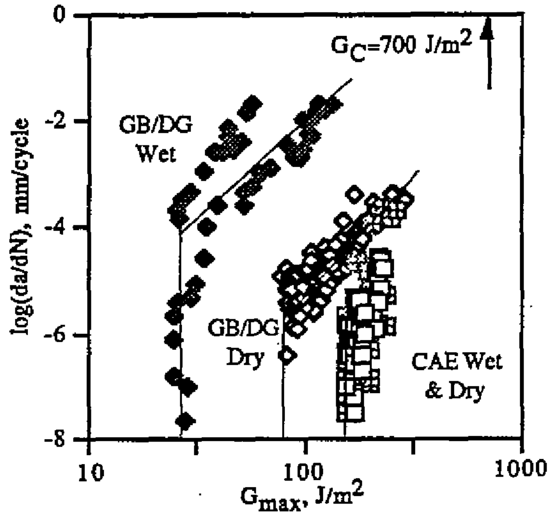

Figure 6: TDCB durability results for 'AV119' adhesive, aluminium alloy adherends.

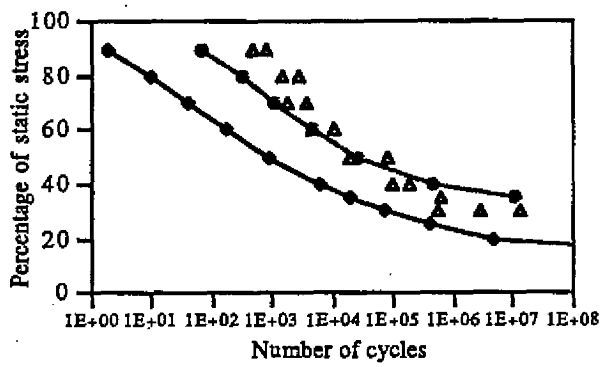

Figure 7: Single lap joints, lifetime prediction: (Δ) experimental, (♦) theory - analytical, (•) theory - finite element. 'AV119' adhesive, steel substrates.

ADHESIVELY BONDED REPAIRS OF FIBRE-COMPOSITE MATERIALS

M. N. Charalambides, A. J. Kinloch and F. L. Matthews

Centre for Composite Materials & Dèpartment of Mechanical Engineering
Imperial College of Science Technology and Medicine, London.

The performance of carbon fibre / epoxy repair joints bonded with an epoxy film adhesive, under static and fatigue loading has been investigated. The joints were immersed in water at 50°C and the effect of the hot/wet environment on the static and fatigue strengths was evaluated. One aim of this study is to determine a failure criterion which will accurately predict the experimental strength of this joint. In order to facilitate this, a parallel study on double lap joints prepared from the same substrate and adhesive as the repair joints, was performed. Static tests on lap joints of various overlap lengths were conducted. The experimental failure loads were used in conjunction with finite element analysis to develop suitable failure criteria.

EXPERIMENTAL

The materials used throughout were Ciba Geigy carbon fibre / epoxy composite (T300/914) and epoxy film adhesive (Redux 319). The effect of the hot/wet environment on the performance of the repair joints was studied by immersing the specimens in distilled water heated at 50°C for various periods.

The repair specimen geometry is shown in Figure 1. One of the adherends, i.e. the parent, was precured according to the manufacturer's specifications. This represents the original material that has undergone damage and is in need of repair. After autoclave curing, the parent plate was machined at an angle of 1.9°. The adhesive and the other adherend, i.e. the repair, were then co-cured under vacuum pressure only, simulating a typical repair procedure used in industry. The lay-up of the parent and the repair was quasi-isotropic, $(\pm45/0/90)_{2s}$, with two extra 0° plies on the upper and lower surfaces of the repair joint.

The composite adherends of the double lap joints had a unidirectional lay-up and were cured in an autoclave according to the manufacturer's specifications. The geometry is shown in Figure 2.

All static tests were performed on an INSTRON tensile testing machine at a constant crosshead rate. The fatigue experiments were performed under tensile load control, at a frequency of 5 Hz and a stress ratio of 0.1.

RESULTS

The static tests results are summarised in Table 1. A small increase in the failure load is observed in the "4 month conditioned" specimens. The failure loads are converted to failure "stresses" by dividing by the cross sectional area of the parent side. For comparison, the failure stress of the parent composite was 611 MPa.

The fatigue data are shown in Figure 3, in the form of S-N curves. Fatigue data for the parent material from reference (1) are also plotted on the same graph, for comparison purposes. It is obvious that there are no significant changes between the "dry" and "conditioned" repairs whereas there is a noticeable decrease in fatigue life when compared to the parent data.

The results from the double lap static tests are shown in Figure 4.

FINITE ELEMENT ANALYSIS

Finite element analysis was performed on the double lap geometry. The ABAQUS software package was used. The applied load was equal to the failure load measured experimentally.

The composite was modelled as a linear elastic orthotropic material. The adhesive was modelled as a linear elastic - plastic material. A pressure dependent yield criterion was used.

In many analyses it is assumed that the joint will fail when a certain stress or strain component reaches a critical value. The latter is usually measured from uniaxial tensile or shear tests. In this study, the FE analysis for the shortest overlap (L = 10 mm) was used to define the critical values of the proposed stress or strain criterion. This was then used in conjunction with the analysis of the longest overlap (L = 80 mm) to predict the failure load for the L = 80 mm overlap. The validity of the criterion was examined using various parameters: von Mises stress, maximum principal strain, equivalent plastic strain, shear strain and shear stress. Errors of 55 - 60 % in the predicted failure loads were observed.

Other proposed failure criteria are based on values of stress or strain acting over a finite distance (2). These state that the largest distance measured normal to the mean direction of the maximum principal stress, in the zone bounded by the ultimate tensile strength of the adhesive, reaches a critical value when the adhesive fails catastrophically. The ultimate tensile strength of 65 MPa was used in the analyses of the shortest (L = 10 mm) and longest (L = 80 mm) overlaps. A spew fillet was introduced in the model in order to be consistent with the work described in reference (2). The critical distance was determined from the L = 10 mm analysis. This was used in conjunction with the L = 80 mm analysis to predict the failure load. The error in the predicted load for the L = 80 mm joint was 68 %.

An alternative criterion is the one proposed by Crocombe (3). This is referred to as the global yielding criterion and it suggests that failure occurs when the path of adhesive along the overlap region reaches a state in which it can sustain no further significant increase in applied load. When this criterion was used for the short overlap analysis an error in the predicted failure load of 30% - 40% was obtained. It was not used for the longer overlap, since yielding in such cases is constrained at the two ends of the overlap region.

Lastly, a failure criterion based on Fracture Mechanics was examined. Short cracks were introduced at the critical end of the adhesive. The J-integral was then calculated for the two overlap lengths. Using the same crack length, a much higher J-integral was obtained for the longest overlap. In both cases, it was predicted that mixed mode loading conditions prevail at the crack tip, with a higher Mode II to Mode I ratio observed for the longest overlap. However, the difference in the mode ratios is not thought to be large enough so as to explain the observed difference between the J-integral values. The critical crack lengths can not be quoted as yet, since Mode II and Mixed Mode tests are yet to be performed on Double Cantilever Beam joints.

REFERENCES

1.Robson JE, "The repair of composite materials", Ph.D. Dissertation, Centre for Composite Materials, Imperial College of Science Technology and Medicine, University of London, 1993.
2.Clark JD and McGregor IJ, *J. Adhesion* 42 (1993) 227.
3.Crocombe AD, *Int. J. Adhesion Adhesives* 9 (1989) 145.

Conditioning	max. load (kN)	"stiffness" (kN/mm)	"stress" (MPa)
"dry"	23.32 ± 1.25	131.13 ± 3.52	526
4 months	29.69 ± 1.41	125.27 ± 5.34	594
11 months	28.65 ± 0.49		546

Table 1: Static tests results of repair joints.

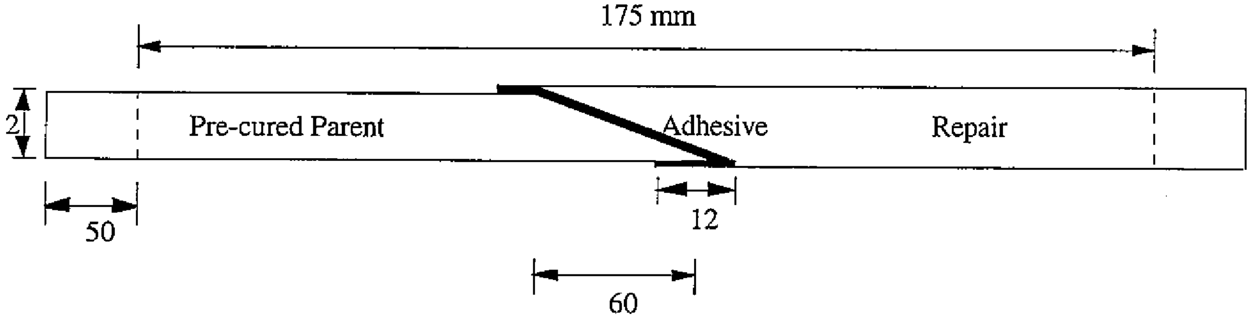

Figure 1: Repair specimen geometry

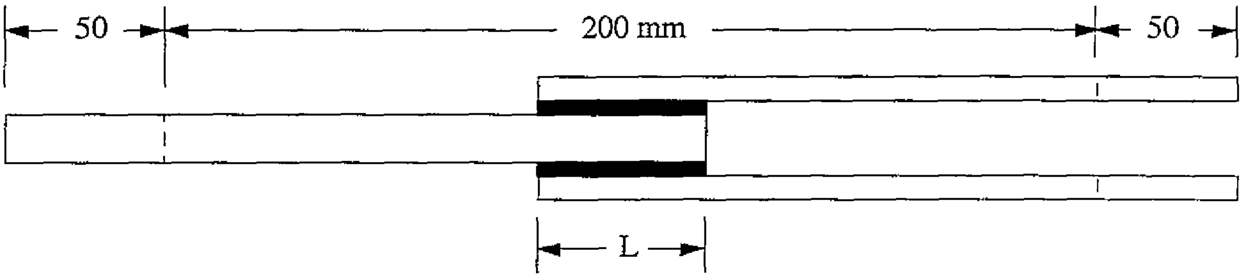

Figure 2: Double lap specimen geometry

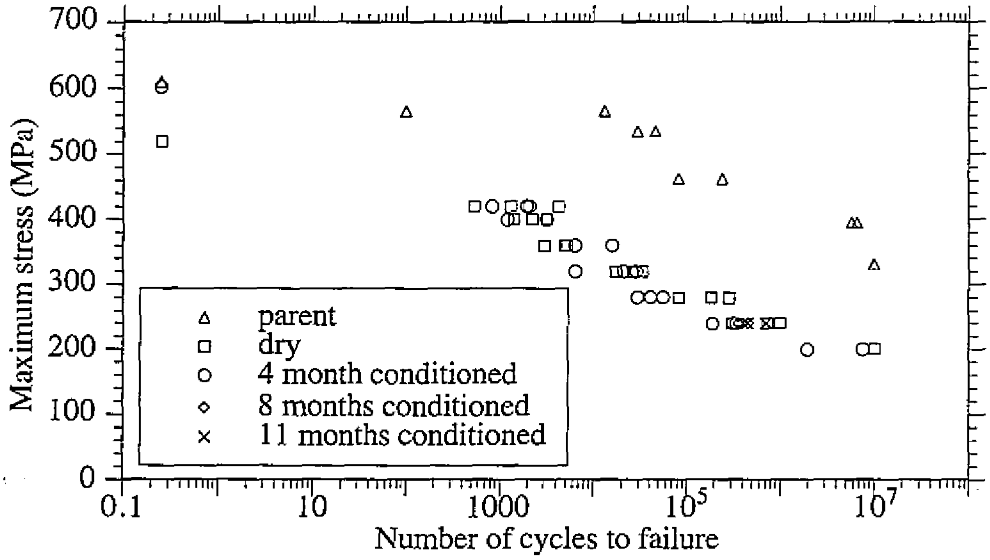

Figure 3: S-N curves for "dry", "conditioned" and parent samples

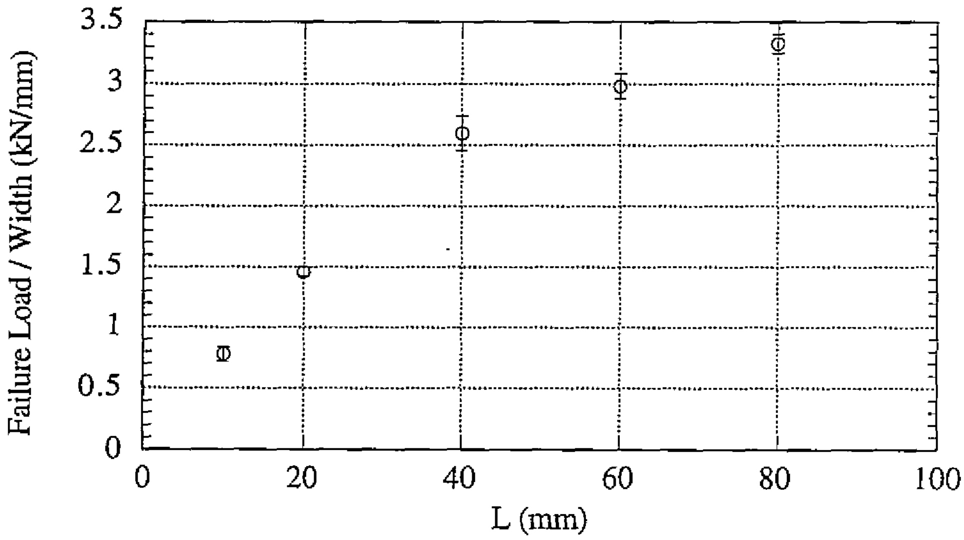

Figure 4: Load per unit length versus overlap length

FATIGUE AND FRACTURE ANALYSIS FOR ENVIRONMENTAL LIFE ASSESSMENT OF BONDED STRUCTURES

J. A. Harris and R. H. Martin
MERL Limited, Tamworth Road, Hertford, Herts. SG13 7DG, UK

Stress Analysis and Fracture in Adhesive Joints
IoM Adhesives Section ,
18th April 1996

INTRODUCTION

An important requirement for the introduction of adhesive joints into engineering structures is a methodology by which the service life of the joints may be reliably assessed, taking into account the expected working environments. Conventionally, durability assessments are carried out by exposing joints to aqueous, high humidity and/or corrosive environments. In some cases, the joints are unstressed and residual strength measurements are made after various times of exposure [1]. Alternatively, the joints are stressed under constant load and the time to failure is measured [2]. The results from such tests are generally only qualitative, giving a ranking for the adhesive systems under the conditions of the test. No quantitative information is derived that can be used for design or life assessment purposes. There is also the danger of 'over accelerating' the test conditions [3] in order to obtain data quickly such that the failure mechanisms become unrepresentative of service conditions and the rankings obtained for adhesive systems are misleading.

OVERVIEW OF NEW METHODOLOGY

This paper gives an overview of ongoing work aimed at developing new life assessment methodology for bonded structures. The particular focus is on the materials and environments associated with automotive structures, however the approach is applicable to other application areas. The method requires an integrated approach to joint testing and analysis and ultimately must be validated by correlation with the behaviour of realistic structures. As part of the programme, a number of elements of testing and analysis are brought together in an integrated way to establish the new methodology. This is shown schematically in Figure 1. The improved methods require 'JOINT FATIGUE PROPERTY MEASUREMENTS'. For many bonded structures, particularly vehicles, the loads of primary importance are the cyclic loads that arise during operation. The interaction of fatigue loading with environmental effects is therefore of primary importance to life assessment Here a relatively simple laboratory test, suitable for typical automotive coated steels, has been developed to: (a) compare the effects of various environmental conditions on adhesive systems, and (b) provide fundamental fracture mechanics data that can be used in the durability and damage tolerance analysis of bonded structures. Some knowledge of the 'BULK ADHESIVE PROPERTIES' is required in terms of elasticity and moisture diffusion (diffusion coefficient 'D' and equilibrium mass uptake M'_{∞}) under various environmental conditions. This is required for modelling purposes using finite element analysis (FEA) and provides insight into the possible degrading effects of moisture from the environment. The use of the 'joint' and 'adhesive' property data is validated by correlating the predicted fatigue behaviour with test data on a relevant structure. This requires 'FEA OF STRUCTURES' and 'FATIGUE TESTING OF STRUCTURES'.

Summarising the approach, for successful and durable bonded structure design, three key requirements must be integrated i.e.: environmental resistance, fracture mechanics fatigue behaviour and finite element analysis of joint design.

FATIGUE & ENVIRONMENT INTERACTION

The strength properties of adhesive joints can be degraded by the effects of moisture ingress throughout the adhesive layer either by loss of interfacial strength and/or by a reduction in the cohesive strength properties of the adhesive. For epoxy adhesives, it has been suggested that interfacial failure occurs when the moisture concentration in the adhesive exceeds a critical local value which can only occur in an environment above a certain critical relative humidity [4 - 6]. In joints that are subject to fatigue loading, it has been shown in tests on double cantilever beam (DCB) type joints [7] that with the ingress of moisture, more rapid crack growth can occur. Associated with this is a change in the mode of failure from cohesive to interfacial. This is illustrated schematically in Figure 2. This process is potentially very damaging because a growing crack provides a direct path for moisture to attack the interface just ahead of the crack tip. The failure process is thus governed by the rate of diffusion of moisture, the rate of crack growth and the rate of reduction in interfacial strength due to the presence of moisture. Such a joint response can be used as input to the analysis of a structure, accounting for the effects of moisture, to assess the life of the structure.

TEST METHODS

One important aspect is the development of a suitable test method and test piece geometry that enables the interaction between environmental and loading conditions to be quantified for typical thin section automotive sheet materials. The quantitative data obtained from such tests may be applied to the analysis of bonded structure and the results correlated with structural tests. If this is done on a fracture mechanics basis, then materials input data is provided for the intrinsic materials relation between fatigue crack growth rate (**da/dN**) and the energy available to cause crack growth, termed the strain energy release rate (**G** for linear analysis and **J** for non-linear analysis). The normal method for this characterisation is to use a DCB test piece which requires thick and even tapered substrate sections to prevent permanent bending of the arms of the test piece. For materials used in automotive body structures a reinforced double cantilever beam specimen (RDCB) has been developed in which the thin gauge material is reinforced by attachment of a reinforcing layer. For the test, use is made of a mechanically operated multi-station fatigue machine. A compliance calibration is performed on the test pieces prior to testing. The method requires little operator intervention, since once set-up, several test pieces can be run simultaneously and the crack length is determined automatically from the compliance measurement.

ANALYSIS

In general, finite element analysis of joints and structures is required so that a number of factors may be investigated through analysis. Ultimately, analytical or empirical solutions may be sought to particular classes of problem. The FEA generally consists of two parts: a stress analysis and a fracture analysis. Stress analysis is used to determine the location of crack initiation where the stresses may be singular.. When the stresses are singular, fracture analysis is used to determine when the crack will initiate. Fracture analysis is also used to determine where the crack will grow and to determine the variation in **G** with crack length **a**. A geometrically non-linear analysis is performed to account for large displacements. The material properties are modelled as linear elastic. The adhesive properties are based on a single part heat curing toughened epoxy. In the analysis it is possible to account for the effects of moisture ingress on the fracture properties by including the effects of moisture on the mechanical properties of the adhesive.

The life of a joint can be assessed by combining the **G** vs. **a** relationship obtained from the FEA with the joint property data obtained as **da/dN** as a function of **a**. This gives the variation of the crack depth **a** with the number of cycles **N**, and when **a** exceeds a critical value the number of cycles to failure N_f is determined.

RESULTS

Values for $D(\theta)$ and $M'_\infty(\theta)$ were derived from mass uptake measurements at the various temperatures of interest (θ) [1]. On the basis of Fickian diffusion, the distribution of moisture concentration through the adhesive layer depends on the product $D(\theta).t(\theta)$. Since M'_∞ does not vary significantly with temperature, then, for the same concentration profile $D(\theta).t(\theta) = D(23).t(23)$ (Room temperature = 23°C). Thus, at an elevated temperature of θ, the diffusion process is accelerated by the factor $D(\theta)/D(23)$. The times at elevated temperature may be equated to the time at 23° C as $t(\theta).D(\theta)/D(23)$. Joint property changes may therefore be compared on the basis of equal moisture concentration profiles using these 'reduced' times.

The deformed mesh from the analysis of a joint in a structure is shown in Figure 3. The model includes a cohesive crack in the adhesive. The crack opening in this case indicates that the joint loading is predominantly peel or mode I. From the analysis, the number of cycles to failure is obtained as a function of the amplitude of the cyclic load applied to the structures. The results are compared with experimental fatigue test data in Figure 4, where the load is expressed in terms of load per unit width of the structure. The agreement between analysis and test is excellent, thus demonstrating the ability of the method to assess the fatigue life of structures.

CONCLUSIONS

A new methodology to assess the life of structural adhesive joints for vehicle body structures is being developed. The methodology requires an integrated approach to joint testing and analysis. A reinforced double cantilever beam specimen (RDCB) has been developed to provide intrinsic joint fatigue property data with thin gauge materials. A validation of the methodology has been presented where good correlation is obtained between analysis and test data for a joint in a realistic structure.

REFERENCES

1. J. A. Harris and P. A. Fay, in proceedings of 18th Adhesion Society meeting (Hilton Head Feb. 1995).
2. R. A. Dickie, M. A. DeBolt and S. M. Ward, SAE TP 950128 (1995).
3. M. Ström and G. Ström, SAE TP 932338 (1993).
4. R. A. Gledhill, A. J. Kinloch and S. J. Shaw, J Adhesion 11, 3 (1980).
5. D. M. Brewis, et. al., Int. J Adhesion and Adhesives 10, 247 (1990).
6. D. R. Lefebre and V.R. Raju in proceedings of Adhesion 90, (Cambridge 10 -12 Sept 1990).
7. M. Fernando, W. W. Harjoprayitno and A. J. Kinloch, to be published Int. J Adhesion and Adhesives.

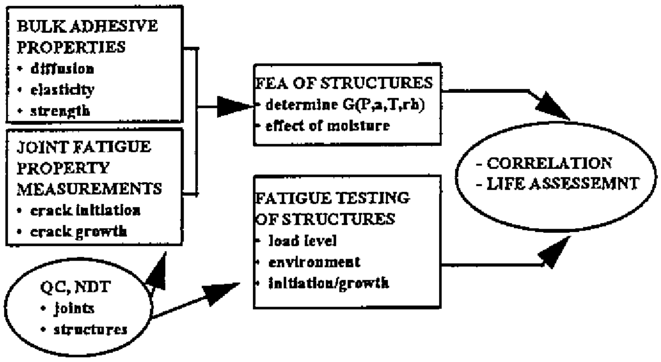

Figure 1 Overview of integrated life assessment methodology.

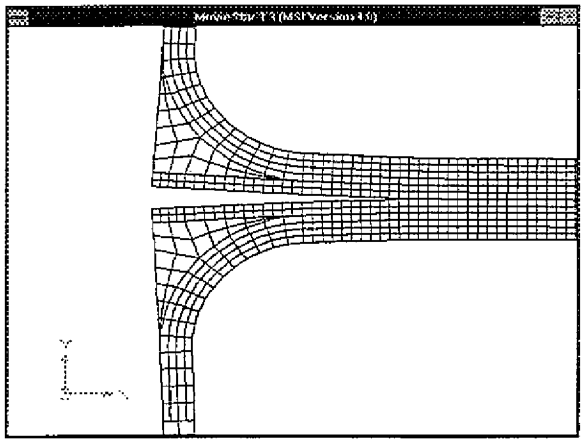

Figure 3 Deformed mesh from FEA of structural joint with a cohesive crack in the adhesive layer.

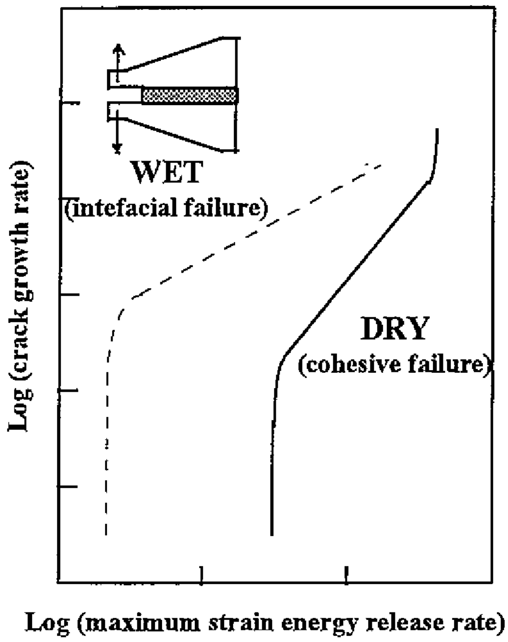

Figure 2 Schematic of the influence of moisture ingress on the relationship between the rate of crack growth in fatigue and the fracture energy.

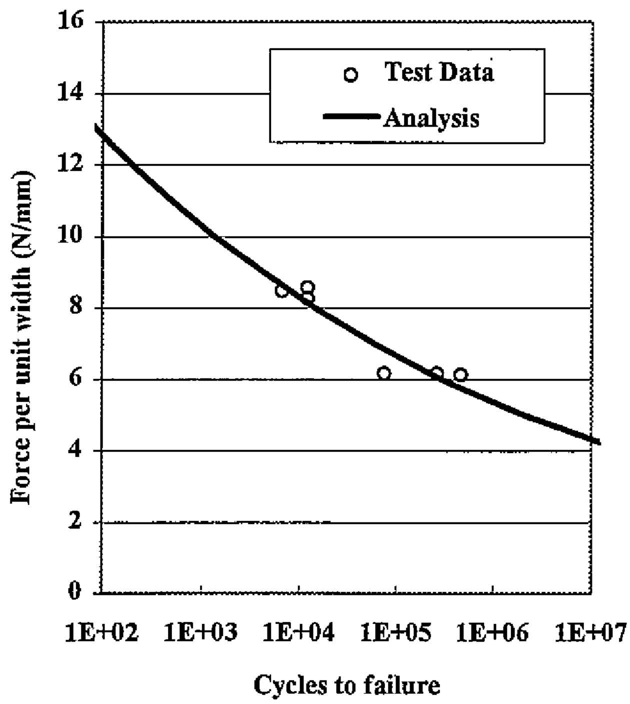

Figure 4 Assessment of the fatigue life of a structural joint under 'dry' conditions.

CREEP AND FATIGUE INTERACTIONS IN ADHESIVE JOINT FAILURE

Crocombe AD, Xu XX, Ge W and Smith PA
University of Surrey
Guildford, Surrey, GU2 5XH

Introduction

Fatigue loading is generally considered to be the most damaging form of structural loading. Adhesives, unlike metals, often exhibit significant rate dependent material behaviour at ambient temperatures. Thus it is not surprising that previous workers[1-3] have reported that the fatigue response is effected by the developed creep strains. This paper reports on some of the work undertaken recently that considers this rate dependency in fatigue tests. Further detail and other aspects of this work can be found elsewhere[4-6]. The paper falls into three main sections covering constitutive adhesive data, fatigue and creep testing respectively.

Characterisation of the adhesives

Two contrasting adhesives have been used in the fatigue testing. Both are cold cure epoxy based adhesives with mineral fillers; adhesive A has no further toughening whilst adhesive B includes additional rubber toughening. Two main forms of tensile test have been carried out on cast flat strip dogbone specimens of bulk adhesive: i) a wide range of constant strain/displacement rate tests on both adhesives and ii) a range of constant stress (creep) tests on adhesive B. Adhesive B exhibited notable differences at the various constant rates used but adhesive A was found to be essentially rate independent, see fig 1. The creep tests, fig 2, reveal the highly non-linear nature of the creep compliance of adhesive B. Data from both these tests are used in subsequent finite element (FE) analyses in the next two sections.

Fatigue crack growth

Fatigue tests have been carried out on both adhesives using bulk compact tension (CT) specimens and steel double cantilever beam (DCB) specimens with various adhesive layer thicknesses. A constant ratio of minimum to maximum load (R) of 0.2 has been used for all tests and frequencies range from 20Hz to 0.02Hz. In all tests the fatigue crack grew in a stable but accelerating manner up to the point of final collapse. Measurement of the crack was achieved using a travelling microscope in conjunction with a fine scale attached to the specimen. Use of a scanning electron microscope (SEM) on both the fracture surface and on the surface normal to the fracture plane (before final failure) showed that crack propagation occurred by filler particle cracking and debonding and subsequent linkage of these micro-damages to form a macro-crack. This mechanism does not appear to change with fatigue frequency.

For bonded joints the energy release rate (G) is conventionally used as a crack driving parameter. The value of G is dependent on the material properties used and the previous section shows that, for adhesive B, these will vary with test frequency. In order to accommodate this effect FE analyses were carried out continually adjusting the material properties until they matched the effective adhesive strain rate measured over a small gauge length of adhesive at the crack tip normal to the adhesive layer. Non-linear analyses showed very little difference between G and the J contour integral and hence G has been used to correlate the FCGR. Using the results from these analyses it is possible to plot the FCGR as a function of G for the various tests undertaken. These are shown in fig 3 for both adhesives. It can be seen that a unique FCGR law appears to be appropriate for adhesive A whilst FCGR in adhesive B appears to be strongly dependent on the test frequency. A significant amount of this dependency is removed when the time rate rather than the cyclic rate of FCG is considered, fig 4. This suggests that creep may be playing a dominant role. FCG is faster in the "tougher" adhesive and has also been found to decrease with increasing bondline thickness. For adhesive A a thickness of 1mm produces the same FCGR as the bulk, for E04 there is still a pronounced difference between the two.

Creep crack growth

To investigate the role of creep in influencing crack growth rate the CT and DCB specimens made with adhesive B were subjected to creep loads that initially ranged up to 80% of their static failure load. Stable crack growth was observed and crack growth rates (CGR) were determined in the same way as the fatigue tested specimens. A molecular model results in a CGR that is an exponential function of the stress intensity factor (K) whilst fracture mechanics results in a power function of K. The data for the CT specimens appears to fit both models equally well although the steep slope, see fig 5, makes it rather restrictive to use when designing for creep loading. Note that K is used as bulk specimens are being considered.

Another possible law for creep CGR uses C* rather than an LEFM parameter such as K or G as a crack driving parameter. This is essentially the rate equivalent of the J integral. Whether C* or an LEFM parameter is most relevant depends on the relative size of the zones around the crack tip dominated by creep and elastic strains. For the case of power law (ie secondary) creep the size of the creep zone, the transition time between elastic and creep domination and the C* value can be determined analytically. Using the straight line (secondary creep) parts of the bulk tensile creep data in fig 2 constants for the power law creep equation have been found. From these it can be deduced that the longest transition time, which occurs for the lowest creep load and the initial crack length appears to be about 45 mins. This is well within the time frame of the creep tests and thus it is possible that C* is a more valid crack driving parameter. Appropriate C* values have been calculated and are also shown in fig 5 where it can be seen that the lower slope makes it much more useful in a design context.

Finally, in order to investigate the causes of creep crack growth, time dependent FE analyses of the CT tests were undertaken. Creep models were fitted to the material data shown in fig 2 and the crack was propagated through the FE model at times corresponding to those observed in the experiments. Various conditions at the tip of the propagating crack are being examined, including COD and the magnitude of the creep strain.

References

1. Harris JA and Fay PA, Int J Adhesion and Adhesives, 12, 9-18, 1992
2. Althof W, Adhesive joints: formation, characteristics and testing, Ed Mittal KL, Plenum Press, 659-677, 1984
3. Marceau JA Mc Millan JC and Scardino WM, Adhesives Age, 21, 37-41, 1978
4. Xu XX, Crocombe AD and Smith PA, Intl J Fatigue, 16, 469-477, 1994
5 Xu XX , Crocombe AD and Smith PA, Intl J Fatigue, 17, 279-286, 1995
6 Xu XX, Crocombe AD and Smith PA, 4th Eur Conf: Adv Matls and Proc, Federation of European Materials Societies, Venice, 1995

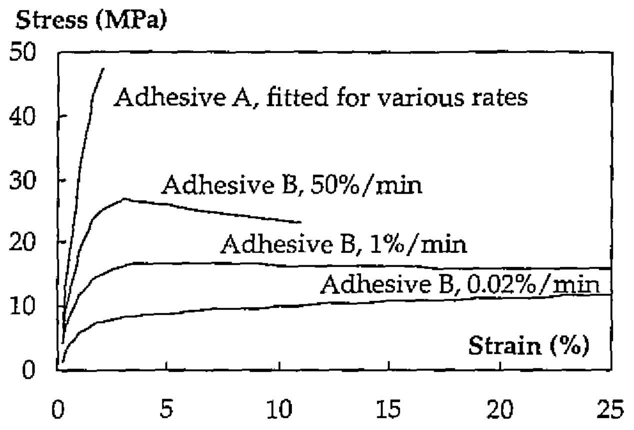

Fig 1 - Stress-strain data for adhesives A and B

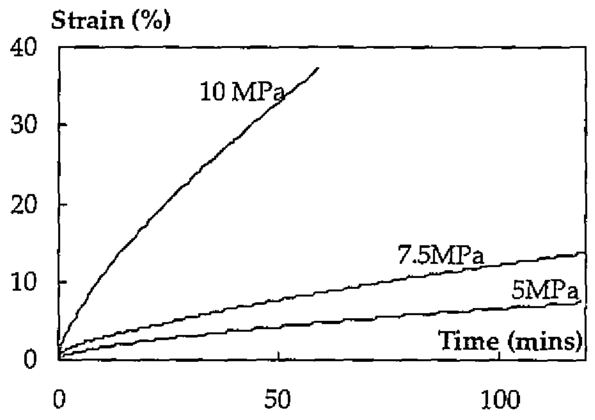

Fig 2 - Creep compliance for adhesive B

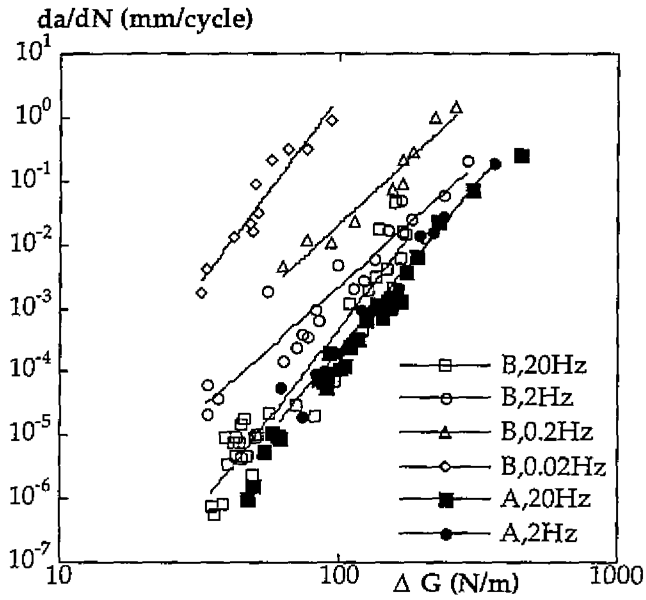

Fig 3 - Cyclic FCGR for DCBs of both adhesives

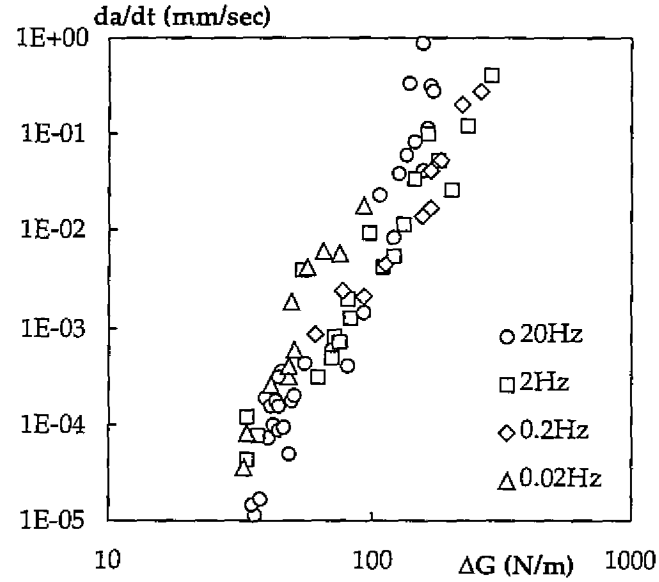

Fig 4 - Temporal FCGR for DCBs of adhesive B

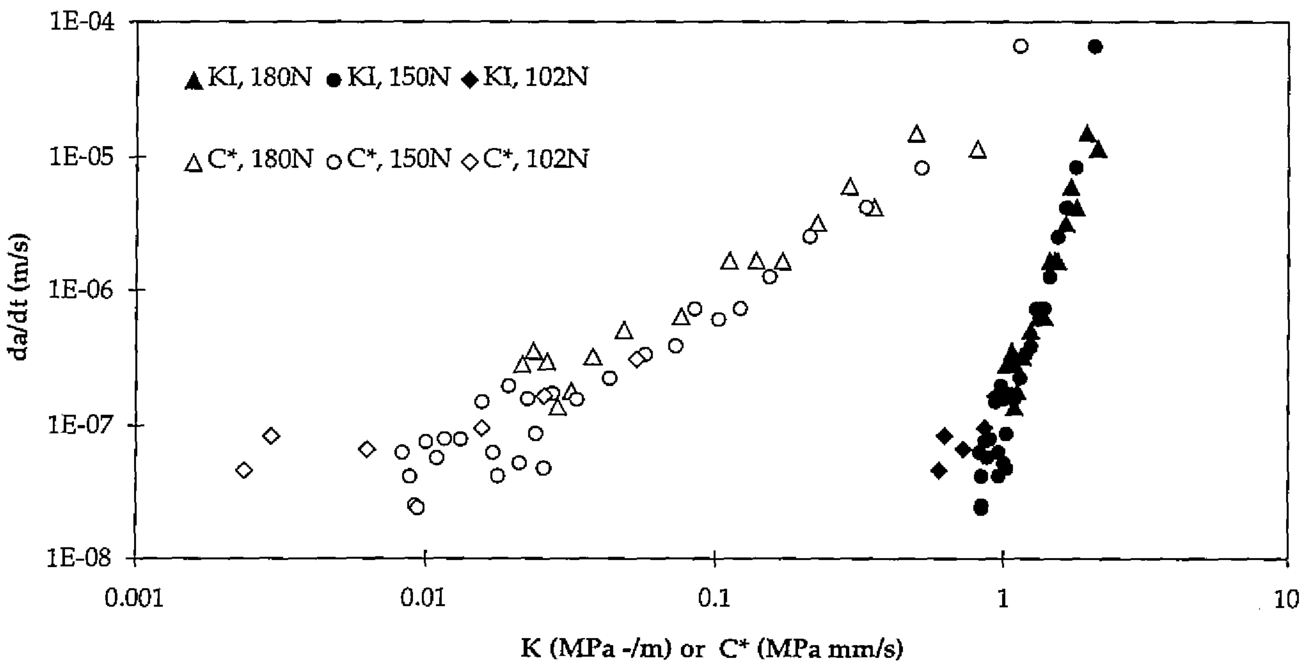

Fig 5 - Creep CGR in bulk CT specimens plotted against LEFM and power law creep parameters