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In Adhesion

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The detectability of kissing bonds in adhesive joints using longitudinal, shear and high power non-linear ultrasonic techniques

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1 Introduction

A large amount of literature has been published on the subject of kissing bonds(1-3), however not all definitions are consistent which has lead to confusion regarding exactly what a kissing bond is and how they are formed. This paper concerns dry contact kissing bonds which are adhesive disbonds in which the disbonded surfaces are compressively loaded providing intimate kissing contact.

Conventional longitudinal wave (4) and shear wave (5) techniques have both been used to inspect imperfect interfaces in metal-metal contacts, whilst recent years have seen an increase in the interest surrounding the use of high power ultrasonic techniques to determine the non-linear behaviour of structures(6-8). This paper looks at the ultrasonic response of dry contact kissing bonds with respect to determining their detectability. The detectability of dry contact kissing bonds is assessed for both longitudinal and shear wave inspection by determining the degree of reflection from the disbonded interface. For the high power technique, the detectability is determined by measuring the change in the non-linear behaviour of the adhesive system.

2 Experimental set-up

2.1 Longitudinal wave and Shear wave inspection

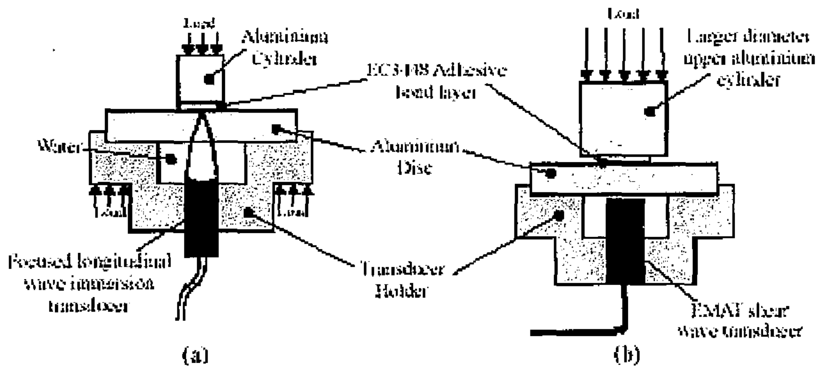


Figure 1. Loading test experimental set-up. Longitudinal (a) and shear (b) wave loading apparatus schematic diagrams

The experimental set-ups for the longitudinal and shear wave inspections are shown in Figure 1. Longitudinal wave testing was conducted using a focused 10MHz wideband immersion probe, focused on the adhesive layer. Shear wave inspection was conducted using a 4MHz Electro-Magnetic Acoustic Transducer (EMAT). The EMATs used produced normal incidence radially symmetric shear waves. The adhesive bond samples were loaded in compression using a mechanical testing machine. The time traces were converted to the frequency domain using a Fast Fourier Transform (FFT) and then processed to calculate the Reflection Coefficient.

2.2 High power ultrasonic inspection

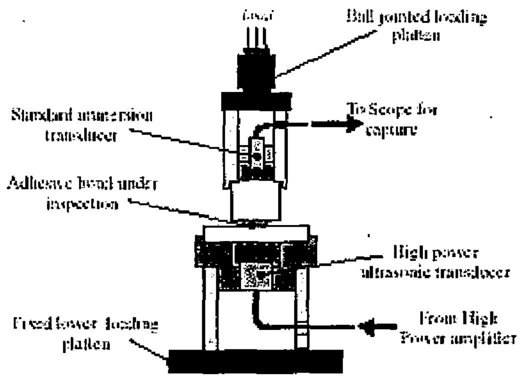


Figure 2. Schematic diagram of high power ultrasonic inspection.

For the high power ultrasonic inspection through transmission was used as shown in Figure 2. A high power ultrasonic transducer was excited using a 6 cycle gated burst at 1.85MHz from a high power amplifier. The signal transmitted across the bond was received by a 5MHz wideband transducer. An FFT was then performed on the signal and the non-linearity of the system calculated by taking the ratio of the amplitudes of the first harmonic and fundamental frequencies (01*AA*).

3 Experimental results

3.1 Longitudinal wave inspection

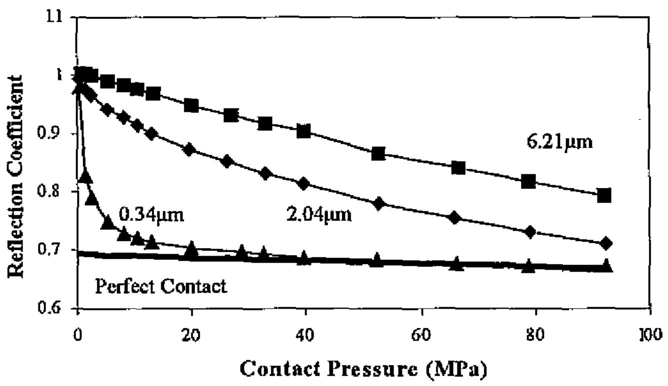


Figure 3. Longitudinal wave loading plots.

Figure 3 shows loading data for three dry contact kissing bonds inspected using longitudinal wave ultrasound. From this figure it can be seen that as the contact pressure at the interface is increased, the reflection coefficient decreases. The reduction in reflection coefficient being due to an increase in the physical contact area. It can also be seen that for a given contact pressure the reflection coefficient is greater for larger surface roughnesses.

3.2 Shear wave inspection

Figure 4 shows the multiple loading cycle data for both a longitudinal and shear wave test. Both samples were produced to the same nominal roughness and the two loading curves calculated for an interrogating frequency of 5MHz. It can be seen from Figure 4 that the form of the two loading curves is the same. However, it is noticeable that the low signal amplitude of the EMAT shear wave transducer creates a much "noisier" load curve than the longitudinal wave immersion transducer.

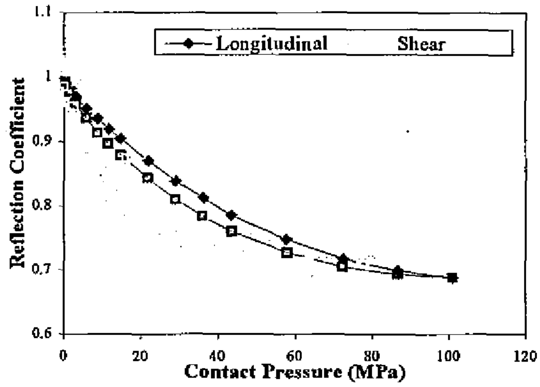
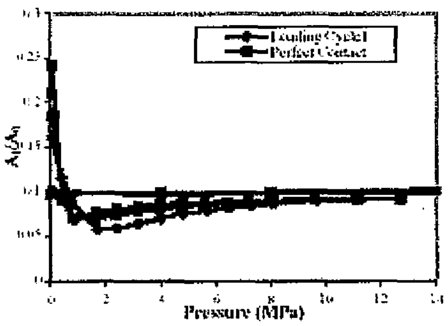


Figure 4. Comparison of shear and longitudinal loading tests.

3.3 High power ultrasonic inspection



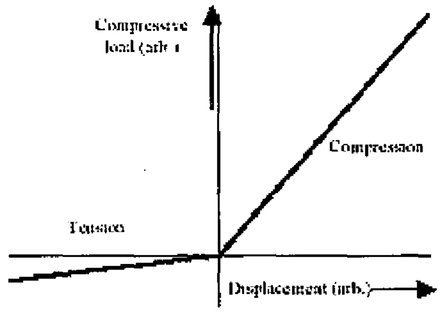


Figure 5. High power ultrasonic response from dry contact kissing bond. Figure 6. Non-linear stress-strain response of clapping contact.

An example of the high power ultrasonic response of a dry contact kissing bond is shown in Figure 5. The plot shows the non-linear ratio plotted against contact pressure for a two cycle loading test. It can be seen from the plot that the non-linear ratio of the system is at a maximum at very low loads. This can be attributed to clapping behaviour of the interface. At low loads the interface will have large areas which are only just or very nearly in contact. When the large amplitude of oscillation is incident on these contact areas, their localised stress-strain curve looks similar to that shown schematically in Figure 6. The large difference between the tensile and compressive stiffnesses results in a highly non-linear system creating significant harmonic distortion in the transmitted signal. As the contact pressure is increased, the percentage of contact area that is only lightly loaded will decrease and hence the non-linearity of the interface will also decrease.

Figure 7 shows the sensitivity of each of the three techniques to the presence of three roughnesses of the disbanded interface. The sensitivity is determined by the percentage of the "well bonded" value for each technique. In the case of longitudinal and shear wave inspection, this will be determined by the perfect contact reflection coefficient whereas in the case of the high power technique this is determined by the inherent non-linearity of the inspection system (i.e. electronic and adhesive non-linearities). It can be seen that the sensitivity of the high power technique drops off very quickly with load whereas the sensitivity for longitudinal and shear wave techniques decreases much more slowly.

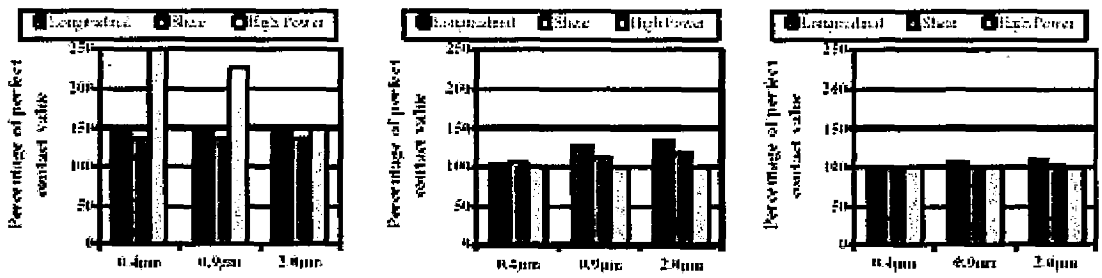


Figure 7a. Sensitivity at 0.04MPa cont. pressure.

Figure 7b. Sensitivity at 10MPa cont. pressure.

Figure 7c. Sensitivity at 50MPa cont. pressure.

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Ultrasonic Inspection of Aircraft Structural Joints

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Abstract:

Using conventional ultrasonic search units, manual inspection of large areas of aerospace structural joints can be a time consuming, tiring and difficult process. There have been many developments towards automated or semi-automated inspection of structures using fixed and portable scanning frames. These often use a water coupled (water jet, bubbler) ultrasonic sensor providing a single or a group of multiplexed channels. Despite relatively high levels of automation the set up and scan time can be considerable.

Airbus recognised the need for a portable scanning system that could be easily used in the field for rapid inspection of aircraft joints and the effectivity of the sealant used, and through a collaborative research project have brought together several enabling technologies to develop an integrated system utilising phased array hardware, high frequency wheel probe technology and high speed data capture. The ultrasonic wheel array sensor instrument (UWASI) has resulted in the delivery of an advanced ultrasonic system that has undergone comprehensive field trials at Airbus sites in the UK and Europe.

This paper describes the scanning technology and its operation from an end-user perspective. Examples and results from applying the system for the inspection of metallic and composite structures are presented.

Failure Analysis of Coatings

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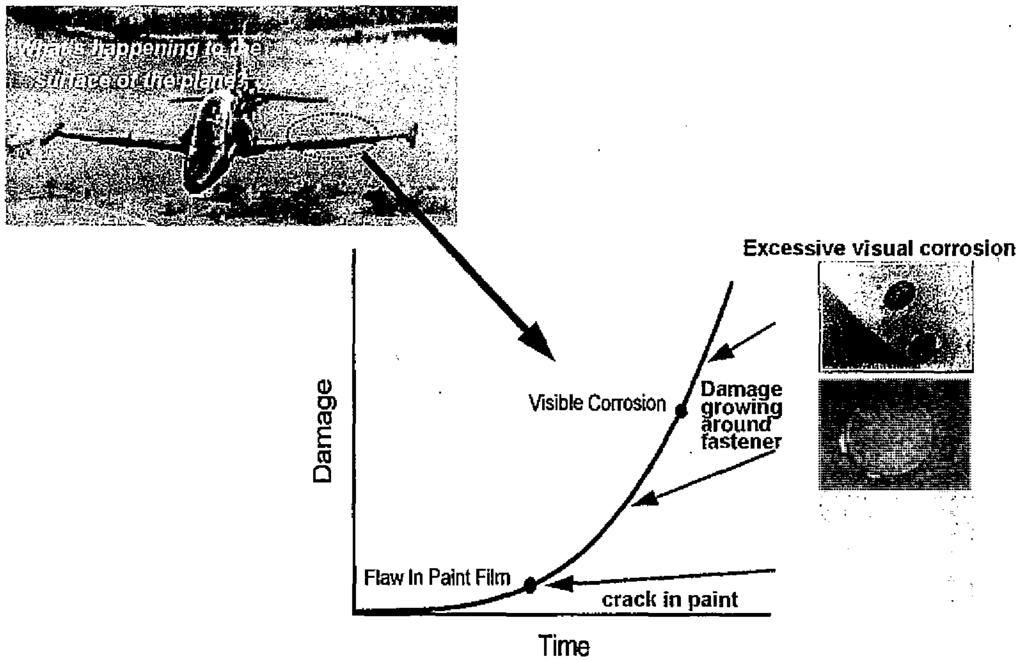

In the case of an airframe, the initial generation of flaws in the paint system are not fully understood. The time from the generation of the first flaw from manufacture to the first critical defect in the paint film has not been studied despite its effect on product performance. There are a number of key parameters that must act in combination in order to induce defects in the coating following operational usage, these include:

- Environmental conditions.
- Operational conditions
- Fabrication issues

In the following work, a range of different types environments were used to test the performance of a range of standard aerospace paints. These results are compared against data obtained from aircraft teardowns and field test data.

The Significance of Defects in Adhesively-Bonded Structures

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ABSTRACT

In adhesively bonded structures, a variety of defects may be present (Adams et al 1997). These defects may be in the form of poor surface preparation, inadequate cure, voids, porosity, cracks and so on. Most of these defects can be detected by one or more NDE techniques. There are several NDE methods, such as ultrasonics, the Fokker Bond Tester, the Tapometer, and so on which can locate defects in adhesively-bonded joints, but it is important to understand the structural significance of these defects. Sometimes, these voids may indicate poor manufacture and inadequate quality control, but there may be little or no loss of strength. On the other hand, the void may lead directly to a reduction in short-term strength.

However, NDE is only one part of assessing if a structure is fit for purpose. Finding defects does not tell us if a structure is otherwise strong enough. It is therefore important not only to detect defects, but also to understand their significance. Fracture mechanics can be of help, but only if the basic mechanics of the component is understood. In long-term applications, fatigue cracks and moisture penetration will lead to very different failure mechanisms, and there is no doubt that long-term performance will be seriously reduced by the presence of voids.

In the case of adhesively-bonded joints, it had long been believed that the presence of defects did not matter provided these were towards the middle of the joint. Work by Schonhorn's group (Wang et al 1972) had frequently been used to validate this. They had showed that, by using high-strength aluminium alloy adherends bonded with a (then modern) structural epoxy adhesive, and inserting a polypropylene disc in the middle of the joint, there was no loss of lap shear strength as the bonded area was reduced to only 40% of the original (undefected) area. However, since Schonhorn's work was carried out, there have been considerable improvements in structural adhesives. We have therefore extended his work by using high-strength steel adherends and a current, commercial epoxy adhesive AV119.

Many joints are assessed by using short-term tests, particularly for quality assurance. In particular, the single-lap joint is widely used to ASTM D1002 specification or similar. The purpose of this work is to investigate the performance of adhesively-bonded lap joints containing known defects so that NDE can better indicate the likely strength of such joints.

When a load P is applied to a joint of width b and length l, the average applied shear stress, τ, is given by

$$\tau = \frac{P}{bl}$$

However, because of differential shear in the adherends (Volkersen 1938), there is a non-linear distribution of these stresses, with peaks at the two ends. Goland and Reissner (1944) showed that because the forces P are not in line, there will be a bending moment M at the joint ends, such that

$$M = \frac{kPt}{2}$$

where t is the adherend thickness and k is the bending moment factor which is a function of the joint parameters and also of the load. In general, k decreases as P increases (Adams et a 1997). The main effect of this bending moment applied to the joint is to create peel stresses (tensile stresses across the adhesive layer) which peak sharply at the joint ends.

Because of these well-known effects in shear and peel, both of which peak at the joint ends, it has long been believed that defects towards the middle of the overlap should have little or no effect on joint strength. If this is true, then the importance to NDE is that detecting voids in the middle of the joint is of no significance, and all efforts should be concentrated in the highly-stressed region at the joint ends.

Adams et al (1997) have discussed the mechanics of bonded joints and have shown that the theories of Volkersen and of Goland and Reissner are sufficient for a preliminary understanding of joint mechanics. However, there are other important factors which need to be considered in real joints. These factors include, in particular, the non-linear yield and plasticity of real materials, both the adhesives and the adherends.

We have used a modern structural adhesive AV119 from Ciba. This material has a tensile strength (and yield stress) of about 70 MPa, and a strain to failure of at least 7% in tension.

The adherends were chosen so as not to yield in the range of forces to be used in this investigation. To check against Schonhorn's results, we also used a low-carbon mild steel which had a yield of 170-200 MPa.

Controlled defects were introduced by inserting PTFE strips symmetrically in the middle of the joint.

For the mild steel adherends, the variation of joint strength with increasing debonded area showed that there is no effect of defect size on joint strength until more than 50% of the bond area has been removed. This is in accordance with Schonhorn's results. However, when adherend plasticity is suppressed, by using the hard steel, there is a clear and almost linear reduction in joint strength with increasing area of debond.

The explanation for these results can be related to the relative plasticity of the adhesive and the adherends. Had we used a very ductile (acrylic or polyurethane) adhesive with the mild steel, it is likely that adherend yield would have ceased to dominate the results. But since the mild steel is very much more ductile than the AV119 epoxy adhesive, adherend yield at the joint end causes failure.

CONCLUSIONS

The significance of these results for the NDE of adhesive joints is apparent when the adherends are made from a material which is not ductile, such as high-strength metals (as used here), or advanced composites (such as carbon fibre reinforced plastics).

The commonly held belief that the important area for strength control in bonded joints is only at the joint ends is seriously misleading as a generality, as it only applies to low yield strength adherends, and not to high-strength materials.

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Predicting the onset of failure in Adhesive Joints

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Finite element analysis can be a very useful aid in the design of adhesively bonded joints. An analysis enables the deformation of the joint to be predicted together with distributions of stress and strain in the adhesive layer. The influence of geometrical features, defined by the shape and dimensions of the joint and the presence of fillets, on stress and strain levels in critical regions of the adhesive can then be rapidly and easily explored. In this way, concentrations of stress and strain can be reduced leading to optimisation of the performance and reliability of the joint.

It is also desirable to use these calculations with a criterion that enables predictions to be made of the circumstances that will lead to the onset of failure in the joint. Several studies of failure in adhesive joints have explored the validity of simple criteria for crack initiation based on reaching a critical level of a component of stress or strain at some location in the adhesive layer. A proper evaluation of these criteria relies on accurate predictions of stress and strain in local regions of the adhesive where failure initiates. If predictions are made using materials models whose accuracy can be low and dependent upon the joint geometry, then this will confuse the identification of a valid criterion.

For reliable predictions, the materials model used by the finite element system must accurately describe the deformation behaviour of the adhesive. Rubber-toughened adhesives are ductile materials that exhibit extensive non-linear deformation before failure. Elastic-plastic models are used in finite element systems for describing this type of behaviour in rigid materials. Limitations in these models when used with adhesives can be demonstrated using results from tests on bulk and butt joint specimens and are associated with the nucleation of cavities in the rubber particles under certain stress conditions. The cavitation gives rise to enhanced plastic deformation through widespread shear yielding in local regions of the matrix adhesive between cavities. This enhanced yielding is not taken into account in existing models, and a new model has been developed for this purpose.

The model takes account of the effect on yield stresses of the replacement of rubber particles by an equal volume of effective cavities. The nucleation is assumed to occur over a critical range of volumetric strain, and a nucleation function has been proposed for describing the dependence of cavity volume fraction on strain. The model is able to accurately predict the deformation behaviour under tension and compression from hardening data obtained in shear.

Test methods and procedures for the analysis of data have been developed for determining the properties and the model parameters required for finite element analyses. The cavitation model and the exponent Drucker-Prager model have then been used to predict stress and strain distributions in joint specimens at the instant when failure is initiated in constant deformation rate tests. Three different geometries have been investigated, lap, T-peel and scarf. Results from these tests have been compared to assess the predictive accuracies of the models and to explore the validity of criteria for the onset of failure in the adhesive.

Stress and strain distributions in the lap and T-peel joints calculated by each model were broadly similar differing mainly in predicted values for hydrostatic stress and volumetric strain. Strain levels in the scarf joint predicted by the exponent Drucker-Prager model were however unrealistically high. Values obtained using the cavitation model at the point of failure of the scarf joint were reasonable but higher than values calculated at failure for the other joints. If these results are accurate, they imply that a criterion based on a critical principal strain or volumetric strain at failure is not feasible.

Calculated peak values for maximum principal stress and hydrostatic stress at the onset of failure are approximately the same in each joint. The locations in the adhesive where the peaks in stress occur are also consistent with sites of failure initiation or the path of the crack. This suggests that a critical stress criterion may be valid, although similar studies on other adhesives are needed to support this conclusion.

ADHESIVE JOINT FAILURES - REALITY AND THEORY

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1. INTRODUCTION

Once the decision has been reached that adhesive bonding is the way to join a component, a key question facing the designer or user of adhesive joints is, "How well can I predict the mechanical performance of my bonded component?" The better the prediction, the more optimised the joint design can be, allowing the final joint to be lighter and more efficient. Without confidence that predictions are going to be close to what happens in reality, designers will - justifiably - minimise any risk and the final joint will not be the most efficient. This presentation presents examples of mechanical tests on adhesive joints and results from a theoretical model, showing that theory and reality can match well enough for users to be confident that the joint will perform satisfactorily.

2. MECHANICAL TESTS

Single lap-shear joints were made, with a width of 25mm and a bonded area of 12.5mm, using two substrate materials, length 100mm, and two types of adhesive. The substrate materials were aluminium alloy (5251 grade), thickness 2.9mm and polymethylmethacrylate (PMMA, Perspex), thickness 1.5mm. The adhesives were a one-part toughened epoxy (ESP4582 from Permabond) and a two-part acrylic (5002 from Permabond). The single lap-shear joints were subjected to a tensile test, and the applied load and cross-head displacement were recorded. The bonded area of the transparent PMMA joints was videoed during the test and the video images were correlated with the load-displacement data, allowing the load at which damage first occurred to be determined (1).

A summary of the results from the mechanical tests is given in Table 1, which presents the average shear stress at failure for three combinations of adhesive and substrate material. For the transparent joints with PMMA and acrylic adhesive, an average shear stress at which the first signs of failure were observed on the video is also given. The failure mode for each of the joint types was determined and is also shown in Table 1.

Table 1 Summary of single lap-shear test results.

Substrate and adhesive	Average shear stress - first damage (MPa)	Average shear stress - failure (MPa) (*s.d.*)	Failure mode
PMMA + acrylic	2.0	3.8 (*0.85*)	Initiation - in adhesive Final - substrate
Al5251 + acrylic	-	21.9 (*0.7*)	Final - cohesive adhesive/near interface
Al5251 + epoxy	-	18.4 (*2.0*)	Final - cohesive adhesive/near interface

3. THEORETICAL MODELLING

The modelling of the mechanical response of adhesive joints has been extensively studied by both analytical and numerical methods (2, 3). The complexity of the geometry of most adhesive joints means that analytical solutions can be hard to use in all but the simplest cases, and numerical methods like finite element (FE) analysis are used extensively. A FE model was developed to represent the three substrate-adhesive combinations, and a novel approach of using a crack-bridging model was adopted. The more conventional approaches with FE models would use fracture mechanics or strength of materials to represent failure. However, these approaches have draw-backs - fracture mechanics needs a pre-defined crack size and strength of materials approaches suffer from a lack of suitable failure criteria. The crack-bridging model made use of large-scale bridging (LSB) conditions, since the damage zone was observed to be similar in size to the overall crack length and linear elastic fracture mechanics ideas would not be applicable.

With LSB the key requirement is to couple the material behaviour with the joint geometry. This was done by converting the normal stress-strain material property data for the adhesives into a force-displacement relationship (4). This relationship was used to define the behaviour of spring elements in the FE model, and it was this use of springs, to represent normal and shear loads in the adhesive layer, that was the novel aspect of the modelling work performed.

The FE model used 4-noded, 2-D plane strain elements to represent the substrates, and separate non-linear spring elements to represent the shear and normal stresses in the adhesive. The results from the FE analysis were processed to give stress distributions within the adhesive layer, and a procedure was developed for defining failure (5), based on the relative magnitude of shear and tensile stresses. From these procedures, a prediction was made of the average shear stress value in the joint at failure, and these values are shown in Table 2.

Table 2 Comparison of predicted and experimental values of average shear failure stress.

Substrate and adhesive	Predicted average shear failure stress (MPa)	Experimental average shear failure stress (MPa)
PMMA + acrylic	3.5	2.0 (Initiation) 3.8 (Final)
Al5251 + acrylic	19.5	21.9
Al5251 + epoxy	18.9	18.4

4. CONCLUSIONS

It is possible to use numerical methods such as finite element (FE) models and analysis to provide reasonably accurate predictions of the mechanical performance and failure of an adhesively bonded joint. The FE analysis methods are not yet standardised and great care does need to be exercised in using an FE model to make predictions about adhesive joint behaviour. However, progress on Guidelines and Standards is being made, by the many organisations and researchers in the adhesives field, which will bring benefits to users and designers of adhesive joints (6).

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