STRUCTURAL VALIDATION
and
HEALTH MONITORING
of
ADHESIVE JOINTS

19th April 2007

Society of Chemical Industry
15 Belgrave Square London

www.uksaa.org/
Programme

10.00 Registration and Coffee.

10.30 In-situ strain and displacement measurement using digital image correlation.  
Jeff Sargent, BAe Systems.

11.00 Experimental and numerical mapping of strain in bonded joints using neutron diffraction and high resolution moiré interferometry.  
Ian Ashcroft, Loughborough University.

11.30 Measuring fatigue damage in bonded joints using the backface strain technique.  
Alejandro Graner-Solana, University of Surrey.

12.00 Modified acoustic emissions for structural damage monitoring of complex structures.  
Christophe Paget, Airbus.

12.30 Lunch

14.00 Disbond monitoring in bonded composite joints using embedded chirped fibre Bragg grating sensors.  
Steve Ogin, University of Surrey.

14.30 Dielectric Analysis of Ageing Structural.  
Dick Pethrick, University of Strathclyde.

15.00 Planes, trains and automobiles: ultrasound technologies for the characterisation of adhesives and the inspection of adhesively bonded engineering structures.  
Richard Freemantle, Wavelength NDT Ltd.

15.30 Inspection of adhesive bonding using pulsed thermography.  
Simon Pickering, University of Bath.

16.00 Discussion, close and coffee.
This one-day symposium is one of an on going series organised by the Society for Adhesion and Adhesives.

Society for Adhesion and Adhesives (SAA) Committee

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The next symposium is due to be held at the SCI on Wednesday 5th December 2007.

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EURADH 2008

ADHESION '08
Tenth International Conference on the Science and Technology of Adhesion and Adhesives
St. Catherine's College, University of Oxford, UK
03 - 05 September 2008

FIRST ANNOUNCEMENT AND CALL FOR PAPERS

Co-ordinated by the Society for Adhesion and Adhesives which is based at The Institute of Materials and organised by IOM Communications Ltd

The scientific committee, which is drawn from specialists well-known to the international adhesion community and is co-chaired by RA Chivers (UK), E Papon (France) and W Possart (Germany), now requests papers on any of these aspects of the science and technology of adhesion and adhesives:

- Fundamental aspects of adhesion
- The science and technology of surfaces
- Bio-adhesion and cellular adhesion
- Properties of surfaces
- Engineering aspects of adhesion and Engineering applications
- Super-molecule structures used in adhesives
- Advances in adhesive materials
- Environmental and ecological aspects
- Mechanical properties of bonded joints including their durability
- Quality procedures, testing and standardisation
- Innovative designs and applications
- Industrial aspects

The Conference programme will give a high priority to poster sessions.

The 7th Wake Memorial Lecture and the presentation of the de Bruyne Medal for 2008, will form the centrepiece of the Conference; previous recipients of both awards can be seen on the 'Awards' page at http:/www.uksaa.org.

Call for Papers
Authors who wish to make a presentation are requested to send a short abstract – a maximum of 300 words (1 page) - in English, by 30 November 2007, by either of following methods.

The preferred method is for abstracts to be sent directly through the Internet: Access the 'Events' page on the IOM3 Website (http://www.iom3.org/events/); click on '2008 Sept' to find the conference entry; click on the conference entry to access the details; scroll down to the line: 'Authors are asked to submit an abstract here' and follow the link to the submissions page.

Authors without Internet access should send a typed copy of their short abstract, together with the relevant section of this form, to: John Bishopp, Star Adhesion Limited, Star House, 40 Station Road, Waterbeach, Cambridge CB25 9HT, UK.

All papers and presentations will be in English and a condition of acceptance will be that at least one author from each paper will pay to attend the conference and present the work.

Publication
The extended abstracts (4 pages maximum) of the accepted papers will be published in the Proceedings of Euradh 2008/Adhesion '08, which will be available in "hard copy" and CD-ROM at the conference.

Important Dates
30 November 2007 Final date for receipt of short abstracts (max. 1 page)
February 2008 Notification of acceptance to authors
1 April 2008 Dispatch of provisional programme and registration document
30 June 2008 Final date for receipt of extended abstracts (max 4 pages including figures)

Conference Venue
The Congress will be held in the St. Cross Building, which is adjacent to St. Catherine's College; situated on the banks of the River Cherwell in the heart of Oxford; the Conference dinner will be held in Trinity College.

Oxford, The City of Dreaming Spires, is famous the world over for its University and place in history. For over 800 years, it has been a home to royalty and scholars, and since the 9th century an established town, although people are known to have lived in the area for thousands of years; Neolithic settlements date back to 4000 BC and popular legend states that the city was founded by the Trojans in 1100 BC. Nowadays, it is a bustling cosmopolitan town; still with its ancient University, but home also to a growing hi-tech community. It is a pleasing mix of ancient and modern, with plenty to do: visiting the many colleges, some of the local tourist attractions or historical
places of interest, dining out in one of Oxford's quality restaurants, enjoying the local music scene, or visiting one of the local pubs, bars or cafes. (Visit: www.oxfordcity.co.uk)

St. Catherine's College was founded in 1962 by Lord Bullock, although it has its origins in a non-collegiate Society which was established in 1868 as a means for the less well-off to study at Oxford. The College's motto - *Nova et VETERA* (the new and the old) - sums up its unique quality among Oxford colleges. While taking much from the best traditions of Oxford, it succeeds in having a much less formal and more relaxed and friendly atmosphere than many other colleges. Designed by Danish architect Arne Jacobsen, its situation and architecture give a feeling of space and light and peace. (Visit: www.stcatz.ox.ac.uk)

Oxford and its Colleges are readily accessible to the traveller by rail with excellent train services from London (Paddington), the South West, South Wales, the North East and the North West (via Birmingham). Oxford is also served by a network of major roads, including the M40, which give good access from much of the country; car parking facilities are available at St. Catherine's. The International Airports at London (Heathrow and Gatwick) both have good rail links with the city; there are also excellent coach links from many major cities and airports.

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John Bishopp, Star Adhesion Limited, Star House, 40 Station Road,
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In-situ strain and displacement measurement using digital image correlation

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Introduction
Quantitative measurements of adhesive/adherend strains and displacements and in-situ imaging under load provide a useful way of understanding the micromechanical behaviour of an adhesively bonded joint. In addition, these measurements are useful as a means for validation of predictive models. Digital image correlation (DIC) methods offer a relatively easy method for obtaining such measurements. Although only of intermediate sensitivity and accuracy the ability to make measurements using relatively unsophisticated hardware with relatively undemanding requirements in terms of system stability gives many advantages over techniques based on holographic or similar methods.

This paper reports on examples from a number of studies using digital image correlation (1,2,3) including validation of predictive models. This shows measurements of adherend displacement and adhesive bond-line strains on single-lap, dcb wedge and “L” and “T” geometry bonded joints subjected to a variety of loading and durability testing regimes.

Experimental method
Experimentally determined in-plane 2D maps of the strain fields and adherend displacement were derived using proprietary digital image correlation software (4). This gave full-field surface displacement vector maps from which surface shear and tensile components (\(\varepsilon_{xx}\), \(\varepsilon_{yy}\) and \(\varepsilon_{xy}\)) were obtained. The software runs on a PC, and although it can be used with any imaging device from which digital images can be derived, e.g. a digital camera, or an SEM, it was used here in conjunction with a small straining stage mounted on the stage of an optical microscope (Zeiss Axioplan). A general image of the loading rig for a “T” specimen on the stage of the optical microscope is shown in Figure 1.

By correlating images taken at zero load with images at successive loading increments, sub-pixel resolution displacement maps (with an accuracy \(\pm 1/20^{th}\) pixel) and strain field maps (with an accuracy \(\pm 0.1\%\)) were obtained of small regions of specimens with a size determined by the field of view of the microscope and the image plane of the camera. As a guide when using a 2.5x microscope objective, a resolution of \(\pm 1/20^{th}\) pixel resulted in an equivalent displacement accuracy of approximately \(\pm 0.2\mu\).

![Figure 1. 3 point straining of an adhesively bonded composite “T” specimen mounted in-situ on the optical microscope stage.](image-url)

Small specimens suitable for in-situ examination on the straining stage of a microscope were prepared from larger 1inch wide specimens by cutting using a precision rotary diamond saw. This usually gave a suitable surface with sufficient contrast to give image correlation. Specimen width ranged from \(\approx 0.3\)mm for the thinnest lap-shear specimens, to \(\approx 3\) or \(4\)mm for the dcb wedge specimens. This width range was dictated by the desire to make specimens as thin as possible, in order that the surface deformation was representative of the deformation likely to occur through the thickness of the specimen, and also by the maximum load (\(\approx 1000\)N) which could be accommodated by the load cell of the
straining stage. An example of a vector displacement and strain map for the fillet region of a single lap-shear specimen derived using digital image correlation is shown in Figure 2.

![Figure 2](image)

Figure 2. From left to right: displacement vector (u) map, strain maps $\varepsilon_{xx}$, $\varepsilon_{yy}$, and $\varepsilon_{xy}$ for the fillet of a single lap-shear specimen. Load (436N/mm), FM73 adhesive, aluminium adherends.

Results

1) “L” type stringer/skin deflection and correlation with predictions.

Stringer/ wing skin “L” type pull-off joints (Figure 3) have been used as a part of bond design strength allowable tests for the BAE Systems Jetstream 41 (Figure 4), where wing loading stresses arise from fuel, air pressure, wing box distortion, skin buckling etc. These joints are bonded using a tough aerospace adhesive, AF163 (G~2000/Jm²).

A closed form analysis using a beam on elastic or plastic foundation was performed on joints with this geometry to help in identifying and understanding those design variables, such as adherend thickness, bond line thickness etc, which controlled strength (1). In addition to validation via strength prediction, it was also valuable to assess details of the predictions at intermediate loads less than the failure strength of the joint. This was undertaken on small specimens of width up to 2mm, prepared from the standard larger width stringer pull-off specimen. Measurements of normal skin and stringer adherend deflection in the bonded section were made using DIC, and their relative displacement was compared against predicted displacements. Figure 5 shows the relative adherend deflection measured using DIC, and Figures 6 and 7 shows a comparison with the predicted deflection at several loads based on an assumption of an elastic and a yielding plastic adhesive foundation respectively. Better agreement was obtained with the assumption of plastic adhesive behaviour, particularly so at larger loads.
2) Lap shear specimens

The above beam theory analysis was useful in showing the need for incorporation of adhesive plastic yield behaviour in order to give agreement between theory and experimental results for adherend displacement. However, although such analyses are useful because they are relatively simple to apply, more sophisticated methods based on FE methods are required in order to model the details of the adhesive behaviour, like that shown, for example, in Figure 2 above. Figure 8 shows a comparison for the specimen from Figure 2 above, between experimental results (A) (derived using DIC) and FE models (B) for the fillet region, at a load of 132N/mm before adhesive damage had occurred. The modelling was undertaken by Crocombe et al. (2) based on a von Mises yield criterion. Whilst detailed differences between predicted and experimental results are evident, the general agreement is reasonable.

![Figure 8](image)

Figure 8. Experimental (A) and predicted (B) strain distribution in the fillet of a FM73/ aluminium single lap joint at a load of 132N/mm, before adhesive damage had occurred.

3) Durability studies and the DCB wedge test.

When designing an aircraft one of the major concerns with a bonded joint is the lowest level to which the strength will fall during the lifetime of the aircraft as a result of adverse effects of the ambient environment. Although extensive long-terms testing are performed on a variety of test geometries, some rapid laboratory accelerated tests are also performed - these frequently make use of the wedge test. A common experimental problem with all DCB type tests is accurately measuring the crack length because significant adhesive yielding and damage occurs at the crack front, making it difficult to define a well characterised and reproducible measure of crack length. This is particularly apparent if the adhesive is tough, like AF163. An example for a wedge test is shown in Figure 9, where the crack length extends over a distance of nearly 3mm.

![Figure 9](image)

Figure 9. A tough structural adhesive like AF163-2K06 exhibits problems with consistent and repeatable measurement of crack length. The image shows a crack extending over a distance of nearly 3mm.

A better defined measure of the crack length would be to use some marker which was consistent and sensitive to crack propagation within the adhesive, but at the same time was
independent of detailed damage. If the adherend displacement is measured, then it is possible
to identify such a marker as the point of zero displacement (Figure 10) for the wedge
specimen from Figure 9. Figure 11 shows the movement of the zero adherend displacement
location immediately after insertion of the wedge and after immersion in water at 18°C. It
was estimated that this procedure permitted a crack length accuracy of approximately
\(\pm 0.1\) mm.

Conclusions

The optical image correlation method provided a consistent, quick and relatively
simple method for making measurements of adherend displacements and maps of strains at
intermediate sensitivity and accuracy in comparison with, for example, holographic or
interferometric methods. This method is applicable in any situation where digital images are
available, but was primarily used here in conjunction with the straining stage on an optical
microscope. It should be emphasised however, that the optical correlation relies on surface
features that remain sufficiently stable over the test period, such that optical correlation is
possible between images. Thus, for example, if the surface was insufficiently stable, and
extensive changes did occur, perhaps as a result of corrosion, then the technique would not
work. It should also be noted that the resolution and accuracy with which measurements
could be made was limited by image contrast, lens distortion giving rise to a spatially non-
uniform images and by spatial linearity and uniformity of the imaging elements at the focal
plane of the camera. It addition, as a general rule when undertaking DIC, apparent
correlations to in plane displacements and strains that arise from out-of plane movement and
specimen rotation also need to be incorporated in order to give accurate measurements. In
spite of these restrictions, however, the method can be used successfully to give detailed
maps of strain and adherend displacement which can be used for validation of predictive
models.

References
1) “Prediction of “Zed” section pull-off loads”, J P Sargent and Q Wilson, Int. J. Adhesion
2) “Validation of predicted adhesive strain and substrate deflection in dry and conditioned
single lap-joints using digital image correlation”, A. D. Crocombe, Y Hua and J P Sargent.
To be submitted.
3) “Durability studies for Aerospace applications using Peel and Wedge Tests” J P Sargent,
Experimental and numerical mapping of strain in bonded joints using neutron diffraction and high resolution moiré interferometry

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Abstract
This paper compares experimentally measured strains generated from neutron diffraction and moiré interferometry experiments with those predicted from finite element analysis. It is seen that, in general, there is good agreement between the experimental and predicted values and that many of the common simplifying assumptions used in the finite element analysis of bonded joints appear acceptable. However, in certain instances differences between the experimental and predicted values were seen that could not be explained by simple manipulation of the model input parameters, indicating further levels of complexity in the real system.

Introduction
The complexity of stresses in adhesively bonded joints has lead to the increasing use of finite element analysis (FEA) when attempting to predict the mechanical response of bonded structures. However, to date there has been little direct experimental validation of the predicted stress distributions. In this work the strain distributions in adhesively bonded double lap joints have been investigated experimentally using neutron diffraction (ND) and moiré interferometry (MI). ND is capable of providing three dimensional maps of the strains in crystalline structures, such as the metallic adherends in bonded joints, whereas MI can be used to generate high resolution maps of the in-plane components of strain at the sample surface. The experimentally derived strain values are then compared with those predicted from a range of FEA models in which various simplifying assumptions are explored. Further details of this work can be found in [1] and [2].

Experimental
The adhesive used in this study was Cytec’s FM73, which is a single part toughened epoxy film, cured at 120°C. The adherends used were unclad 7075 T6 aluminium alloy (Al) and unidirectional IM7/8552 carbon fibre reinforced polymer (CFRP). The Al was pre-treated by chromic acid etching prior to bonding whilst the CFRP was grit blasted and solvent cleaned. Two types of double lap joint (DLJ) were used in the experimental programme, one with only Al adherends (Al-Al joints) and another with both Al and CFRP adherends (Al-CFRP joints). The sample dimensions for each joint type are shown in figure 1.
Figure 1. Joint dimensions. FOV indicates the field of view in which the high resolution moiré interferometry measurements and FE predictions were performed.

Neutron Diffraction
ND experiments on Al-Al joints were carried out using the ENGIN-X diffractometer at the ISIS spallation source in the Rutherford Appleton Laboratory in the UK whereas the ND experiments on the Al-CFRP joints were carried out using the REST diffractometer at the NFL laboratory in Studsvik, Sweden. In the ND method, strain is measured by looking at the shift in the diffraction angle, \( \theta \), of Bragg planes caused by strain induced changes in the crystal lattice spacing. The shifts in strain are measured relative to an unstrained part of the sample. In these experiments the limited beam time means that a trade must often be made between strain resolution, which improves with increased gauge volume, and spatial resolution. In this case slits were used to give gauge volumes of between 1 and 5 mm\(^3\).

Moire Interferometry
MI has the advantage over speckle interferometry that large displacements and rotations can be tolerated that cause speckle decorrelation. However, the disadvantage is that a diffraction grating must be replicated on the surface of interest. In this case a reflection, crossed line, 600 lines/mm diffraction grating was replicated from an aluminium-coated grating mould onto one side of each DLJ. Two different interferometers were used in this work: a laboratory instrument that was set up on a vibration-isolated table and used collimated illumination and a portable instrument using uncollimated illumination that was designed so that measurements could be made simultaneously with the ND experiments. The sample grating was imaged with a high speed camera and the magnification of the system used to change the field of view and spatial resolution of the system. Hence both large field of view experiments could be undertaken for comparison with the ND measurements and small field of view experiments could be carried out to compare with the FEA predicted strains in the adhesive layer. The location in which the high resolution experiments were made can be seen in figure 1.
Results

Figure 2. Longitudinal strains in centre of (a) middle adherend and (b) upper adherend in Al-Al double lap joint with a load of 10 kN. Comparison of FEA and ND results.
Figure 3. Longitudinal strains in centre of (a) middle adherend and (b) upper adherend in Al-Al double lap joint with a load of 10kN. Comparison of FEA and MI results.
Figure 2 shows a comparison between ND measurements and FEA predictions of longitudinal strain along the centre of the middle adherend and close to the centre of the outer adherend of the Al-Al DLJ. It can be seen that the results from two FEA models are shown, the first an idealised plane strain model and the second a 3D model in which certain geometric irregularities such as adherend offset and non-symmetric adhesive fillets have been included. It can be seen that agreement between the predicted and measured values is generally good, with best agreement being seen with the less idealised model. The biggest difference between the two sets of results is in the middle adherend between 5 and 12mm. This was also where the biggest difference was seen between MI and FEA results for the
same joint, as seen in figure 3, indicating this may symptomatic of a real anomaly in the experimental test piece. Altering such standard FEA inputs as material properties, geometry and boundary conditions was unable to improve the results here without compromising results elsewhere. This may be indicative of some non-visible damage or irregularity in the joint. ND is also capable of measuring residual strains in bonded joints and this is illustrated in figure 4 in which the thermal residual strains derived from curing the adhesive at elevated temperatures can be seen. In this case there is considerable scatter in the ND data but again, in general, it can be seen that there is good agreement between the experimental and predicted values.

Figure 5 shows an example of the comparison between high magnification moiré interferometry and FEA in the region of the theoretical singularity where the corner of the adherend is embedded in the adhesive layers (figure 1 shows the location of this field of view with respect to the full joint). It can be seen that the expected area of high strain is seen in the adhesive adjacent to the adherend corner and that there is excellent agreement between the FEA and MI. It should be noted, however, that this is not always the case. For example, with CFRP adherends, in which the material is less uniform and prone to internal flaws and irregularities, significant differences can be seen between the measured and predicted strains. There is also the issue that geometry in the FEA model is based on external measurements only and in general geometry is not varied in the z-plane of figure 1 in order to simplify the meshing of the 3D models.

References

Measuring fatigue damage in bonded joints using the back-face strain technique

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1 Introduction

The use of adhesives has increased during recent years. They offer many advantages over other joining methods like welding or riveting. They are light, easy to apply, have a better stress distribution and are affordable. These characteristics make them very suitable in the aerospace and automotive industry, where high strength bonds are required.

Understanding the fatigue characteristics of the adhesives is very important because fatigue causes the majority of failures in service. The existing techniques used to quantify fatigue in adhesive joints are limited, especially when measuring the initiation phase. This paper outlines work that has been done using a technique known as back-face strain to quantify fatigue damage in bonded aluminium single lap joints.

The back-face strain technique, which has also been used by others [1-2], is an effective method for measuring fatigue initiation and propagation. This system works by installing strain gauges on the surface of a bonded joint adjacent to the site of potential fatigue damage. This measures the change in back-face strain as the damage evolves (Figure 1). The location of the gauge is critical, it can be shown that the maximum sensitivity can be obtained by locating the gauge just inside the overlap region of the joint. In the testing reported here, six gauges were placed 1mm inside the overlap region. The advantage of using such a high number of gauges is that they allow greater accuracy when detecting the spatial evolution of fatigue initiation within the joint.
2 Experimental

The single lap joints tested were constructed from aluminium alloy and FM73M adhesive. Two types were built, the first with 2014-T6 aluminium, and the second with 7075-T6 aluminium. The main difference was the substrate thickness, 2mm for the former and 3.14mm for the latter. The overlap length was the same, 12.5mm and the bondline thickness was around 0.2mm.

The fatigue tests were carried out in load control with a stress ratio $R=0.1$ and a frequency of 5Hz. The maximum fatigue load was set to a percentage of the static shear stress ($t_s$). The load-life curve obtained by testing a number of specimens can be seen in Figure 2. The back-face strain was recorded during these fatigue tests and a typical plot showing the variation with fatigue cycles can be seen in Figure 3. The change in back-face strain during the initial part of the test was rather limited, then a transition region occurred and the change increased exponentially. This is in agreement with previously
published data [3]. The peak in the back-face strain curve that was shown in Figure 1 can be seen towards the end of the fatigue life in Figure 3.

![Load-life curve for the adhesive joints tested.](image1)

**Figure 2:** Load-life curve for the adhesive joints tested.

![Typical back-face strain readings from a fatigue to failure test.](image2)

**Figure 3:** Typical back-face strain readings from a fatigue to failure test.
Limited-damage tests were undertaken to observe how the damage developed. The test was run until a certain increase in back-face strain had been reached. The increase is based on the data from the fatigue to failure tests, such as that shown in Figure 3. The overlap region was then sectioned, polished and inspected in a microscope, Figure 4. The damage always initiated in the fillet, as seen in Figure 4.

![Damage in fillet](image)

**Figure 4: Damage in fillet.**

![Damage map for the adhesive joints tested](image)

**Figure 5: Damage map for the adhesive joints tested.**
From such tests a damage map can be produced showing the relationship between change in back-face strain and the extent in damage (Figure 5). A damage scale was developed to characterise the damage, 0 representing undamaged and 5 totally damaged. The damage appeared as a change in colour intensity of the adhesive. Cracks were only seen in specimens that were tested almost to failure.

3 Modelling

One of the main aims of this project was to use the experimental back-face strain data to validate fatigue damage models for the adhesive. ABAQUS was used to develop 2D and 3D models of the joints. Initially 2D models were used because they were less computationally intensive. Later 3D modelling was employed because it gave more data, such as damage growth across the width of the joint. Crocombe et al [4] also used a similar approach in previous work.

The damage model was defined in terms of the adhesive principal strain $e_i$ as

$$\frac{dD}{dN} = be_i^n$$ (1)

where $D$ is the damage ranging from 0 (undamaged) to 1 (fully damaged). As the damage increased the Young's modulus of the adhesive decreased, thus the strain increased until deformation caused joint failure.

Initially a one phase damage model was used (Eqn 1). This was found to give an excellent fit to the experimental back-face strain data at a given level of load (Figure 2). The transition region observed experimentally was found to occur when the ends of the overlap just reached the fully damaged state. Although the fit to the experimental data was excellent at a given level of load the same parameters do not produce the load-life response shown in Figure . To accommodate this, a 2 phase damage model is being developed.
4 Conclusions

The back-face strain technique is an efficient method to monitor fatigue initiation and propagation. The trend observed in all experimental tests was very similar, initially there was very little change in back-face strain, this was followed by a transition region and an exponential increase in the change rate. The back-face strain data could be correlated well with the measured damage, which always initiated in the fillet and appeared as change in adhesive colour intensity.

The one phase damage model fitted very well the experimental data at a given load, but if the same damage parameters were used it was limited when applied at different loads. A more advanced 2 phase damage model is being developed. Future work will include improving the 2 phase damage model and testing it against fatigue data obtained using different stress ratio.
5 References


The present paper focuses on the use of acoustic emission (AE) equipment Vigilant (see Figure 1) for locating structural damage in complex structures (see example in Figure 2), such as aeronautical structures, and assesses structural changes in joints or bonded repairs using the Ultra Electronics and Airbus equipment called Vigilant.

Before having a tool able to monitor complex structures, this paper is studying the case of AE sensor disbonding or badly bonded, so that the data collected by the Vigilant equipment can be trusted. The first results showed that it is possible to determine some disbonding from the coupling between the Vigilant sensors and the structure. However, these results remain quantitative rather than qualitative.

Further investigation was conducted on structural bonded joint to understand whether the quality of the bond-line can be continuously assessed and to determine possible performance limits using the Vigilant equipment at that phase of the investigation. The results are promising although compromise between the distance between sensors either side of the joint was identified as crucial to have a reliable technique.
Monitoring of aircraft structures can be a difficult task and therefore a series of algorithms have been created to be able to unambiguously locate damage in such a complex structures, as shown some results in Figure 3. Indeed the figure demonstrates 100% reliability in locating structural damage during a two-year period of a full-scale fatigued specimen.

The Vigilant equipment was installed on complex structures in many occasions on many flying platforms. Figure 4 shows amongst the first implementation of Vigilant for long-term flight trial.

Figure 3: Example of damage location using Vigilant equipment
Figure 4: First long-term flight trial of Vigilant equipment
Disbond monitoring in bonded composite joints using embedded chirped fibre Bragg grating sensors

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Disbond initiation and growth in either quasi-static or fatigue loading in adhesively bonded structures is a continuing concern. There are a number of techniques which potentially can detect such disbonding (including ultrasonic, thermographic, backface-strain and optical techniques). This paper will present recent work on a novel optical technique using chirped fibre Bragg gratings (CFBGs) which can both detect disbond initiation and monitor disbond growth to within about 2 mm (depending on sensor position and joint materials). In this technique, the optical sensor is embedded within a composite adherend, and not within the bondline, and the method can be used for composite adherends bonded either to other composites or to other materials (e.g. composite/aluminium joints). As the sensor is embedded within an adherend, it cannot act as the site for defect initiation within the joint. In work carried out to date, we have shown that both disbond initiation and disbond growth due to fatigue loading can be identified clearly in a single lap joint by simple changes to the reflected CFBG spectrum.

Chirped fibre Bragg gratings are relatively new optical components for applications in structural health monitoring compared to uniform fibre Bragg gratings [1,2], and hence require a little explanation. A comparison of the reflected spectra from the two types of fibre Bragg grating is shown in Figure 1. For a uniform FBG, a uniform spacing of the periodic variation of refractive index in the core of the fibre (the "grating") reflects light so that the reflected light is centred on a particular wavelength that is related to that grating period (Figure 1(a)). A change in the grating period due to a uniform strain produces a proportional shift in the peak wavelength of the reflected spectrum – it is this shift in the peak wavelength that is used by companies marketing FBG technology to monitor strain changes. By contrast, a chirped fibre Bragg grating, having a linear variation of the grating period along its length, reflects a range of wavelengths with approximately uniform intensity when unloaded, or when subjected to a uniform strain field (Figure 1(b)), and the spectral bandwidth of the reflected spectrum is directly related to the sensor length. A disruption to a uniform strain field, due to disbond initiation and growth, for example, alters the grating period at the location of the disturbance to produce a characteristic perturbation in the reflected spectrum from which the disbond front position can be located.

![Figure 1. Schematic grating period and reflection spectra of (a) uniform FBG, and (b) CFBG.](image-url)
Figure 2. Example of monitoring of disbond growth in a transparent GFRP-GFRP bonded joint.
(a) – (c) Disbond growth at 9,000, 10,500 and 13,400 cycles - the arrows indicate the disbond position being monitored; (d) reflected CFBG spectra at the same number of cycles - the arrows indicate the movement of the dip in the spectrum which is closely related to the disbond position.

Figure 2 shows an example of a disbond growing between two transparent glass/epoxy composite adherends which have been used to manufacture a single lap joint (in these figures, the lower disbond front position in the photographs, which is the disbond being monitored, is slightly out-of-focus and is indicated by arrows). In the case of composite-composite bonded joints, such as this, the reflected spectra are recorded with the joint under a small load (which in practice could be the self-weight of the structure). For a transparent joint, as in Figure 2, measurements of disbond growth obtained using the CFBG sensor are in agreement with visual observations of disbond growth within the joint to within about 2 mm [3], and the observed spectra are in good agreement with theoretical predictions [4].

Recent work [5] has shown that disbond initiation and growth for adherends with different coefficients of thermal expansion (e.g. composite-metal joints) can be monitored, even with the joint unloaded. This is related to the relaxation of thermal residual stresses during disbond growth for joints cured at elevated temperatures. For example, Figure 3(a) shows the movement of a perturbation in the reflected spectrum caused by the growth of a disbond in a GFRP-aluminium single lap joint and Figure 3(b) shows good agreement between the CFBG measurements and direct observations of the position of
the disbond. Again, changes in the reflected spectra as the disbond grows are in good agreement with theoretical predictions [6].

![Disbond length from photographs (mm)](image)

Figure 3. Changes in the reflected spectra with disbond propagation in a metal-composite joint.
(a) Reflected spectra taken with the joint unloaded after 7,000, 8000 and 10,000 cycles.
(b) Comparison of disband length measured using the CFBG sensor with direct observations.

It can be concluded from this work that disbond initiation and disbond propagation can be monitored using CFBG sensors embedded in composite adherends; if the CFBG sensor extends the full length of the overlap of a single lap joint, disbond development at either end of the overlap length can be measured. For adherends with the same coefficients of thermal expansion, disbond initiation and subsequent growth can be monitored with the joint under a small load. When the adherends have different coefficients of thermal expansion and the bond has been formed at an elevated temperature, the joint does not need to be loaded.

References:
Dielectric Analysis of Ageing Structural Adhesives

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Introduction
Adhesive bonding is a widely used method of joining structures when weight is an issue. Adhesives are used widely in bonding metal structures; as in the case of aircraft, cars and various forms of white goods. Carbon fibres structures are often fabricated by bonding preformed structures to create hollow formed light weight components; e.g. tail planes, wings etc in aircraft and reinforcement of metal structures by bonding external CFRP plates. Dielectric analysis has two roles to play in the non destructive examination of such structures. Firstly, it can be used to monitor the cure process and ensure that the structure has developed the required mechanical properties for its particular use. Secondly, it can be used to monitor the changes which are occurring in the adhesive bond line as the structure is used. In this short review both aspects will be briefly considered.

Cure Monitoring
The majority of structural adhesives contain a polar component. The process of curing the material leads to inhibition of the free motion of the monomers which form the adhesive and eventually a glassy phase is formed. In the bonding or composite fabrication process it is important to be able to assess the point at which the resin has changed from being a free flowing liquid to a crosslinked gel and then subsequently to a vitrified glass. The dielectric technique has the capability of providing this information.

i) Free flowing liquid to gel phase structure.
Observations of the viscosity changes which occur on cure can be illustrated by the case of Triethylene tetramine (TETA) cured with an epoxy resin, Figure (1).

As the temperature is increased so the rate at which the viscosity increases rises. If we study the changes in the dielectric relaxaion behaviour of the resin we find that there are certain characteristics changes which can be used to probe the curing processes occurring in the matrix, Figure (2).
resistivity varies linearly with time the viscosity shows a non linear variation. However over a significant range of the cure process there is parallel change in the data which allows the dielectric technique to be usefully used to monitor cure.

Figure (3) Variation with time of the resistivity measured at 1Hz and viscosity of same system at 40°C.

Studies of Adhesive Bond Ageing
The typical adhesive bond mimics a simple capacitor at low frequency. The substrate is usually sufficiently conductive to be used as an electrode and the adhesive is sandwiched between and forms the dielectric. This is true for both metal bonds and CFRP. At high frequency, the bond will look like a delay line and it is possible to propagate an electrical wave down this structure. Two types of measurement can be made; firstly frequency domain measurements and these are used to identify the changes in the relaxation behaviour as the moisture enters the bond line. Water entering the resin can be dispersed as molecular entities which tend to be associated with polar hydroxyl groups and lead to plasticization of the matrix. Water can also aggregate and form clusters in micro-voids. This water will not plasticize the matrix and has little effect on the mechanical characteristics of the resin. A feature has been identified which appears at approximately 3 MHz and is associated with the conversion of surface aluminium oxide into hydroxide. This feature is very useful for the study of the changes which occur to the bond in terms of destabilization of the adhesive – adherent interface. A more detailed discussion of the bond ageing is presented in the next paper.

Time Domain Reflection Measurements
If an electrical pulse is sent down the strip line reflection will be observed at points where there is an impedance change. The impedance change may be associated with a change in the cross-section of the adhesive or a change in the dielectric nature of the material which can be associated air voids, disbanded regions and in some cases kissing bonds. Study of the time domain traces can provide useful information on the changes which are occurring to the joint as it ages. The movement of the peaks in the time domain is determined by the changes in the average dielectric permittivity at high frequency and maps closely on the water absorption data.

Combining the frequency and time domain data it is possible to determine the geometrical structure of the bond line. In practice, it is very unlikely that the bond line will correspond to two parallel electrodes and there will be both variations in the bond line thickness and the width of the bond line. A mathematical analysis of the wave propagation combined with a fitting routine has allowed the prediction of the bond line structure without prior knowledge of the structure. Two examples of the results which have been obtained are presented in Figure (4).

A close inspection of the plots indicates that at the ends the fits of the data are worse than in the centre. This problem is associated with the problem of accurately prediction the electrical characteristics of the connector between the bond line and the instrument used for the measurements. It has been found that by the introduction of a phase shift into the data a better fit can be achieved which is very close to the physical measurements. This study indicates that it is possible to obtain geometric data from the dielectric data which can be used to identify where the changes in the bond are occurring on ageing.

The improved analysis of the data which is now possible allows quantification of the changes which are occurring in the resistivity of the surface layer. This resistivity is related to the state of the oxide layer and hence is an indication of corrosion at the interface, figure (5).

The variation of the permittivity and loss are indicators of the water ingress into the resin layer and the variation of the surface oxide layer. It is clear that in the later stages of ageing there is significant change in this oxide layer reflected in the change in the resistivity. The changes in the oxide layer often parallel a decrease in the mechanical strength of the joint and a change from adhesive to cohesive failure.

The dielectric method presents a very useful method of non destructively examining adhesive bonded structures.
Extended Abstract

Planes, trains and automobiles: ultrasound technologies for the characterisation of adhesives and the inspection of adhesively bonded engineering structures

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Summary
The aim of this paper is to outline current research and industrial methods for the analysis and inspection of adhesively bonded joints using standard and state-of-the art ultrasonic equipment. Techniques for the analysis of the adhesive material (for example cure monitoring) and the validating the integrity of the bond (for example bond geometry, void detection) will be presented and placed in the context of the requirements for production and in-service inspection of bonded assemblies in a range of industries.

Ultrasound and adhesive materials
Ultrasound is one of the primary technologies for the non-invasive investigation of engineering structures and its use for non destructive testing (NDT) of bonded aerospace structures is well established. Beyond the aerospace industry, the use of adhesive bonding technology has increased dramatically as designers start to employ lightweight materials to deliver higher performance structures.

Ultrasound is an attractive technique because the propagation of ultrasonic waves can be related to the mechanical properties (elastic moduli) and the physical characteristics (porosity, fillers, stoichiometric ratio) of the materials under investigation. For instance the relationship between ultrasonic compression wave attenuation (and velocity) and the development of the shear modulus in an adhesive during cure is well known [1],[2] as illustrated in figure 1.

![Figure 1: Changes in ultrasonic absorption in adhesive materials with different hardener/resin ratios as a function of cure time.](image-url)
Adhesive bond inspection
Ultrasonic waves also interact strongly with discontinuities at interfaces making the detection and sizing of interfacial defects (lack of adhesion and delamination) possible.

The recent development of portable high resolution industrial ultrasound imaging systems has enabled rapid inspection of bonded joints as part of production QA or in-service testing to provide an 'ultrasonic photograph' of hidden interfaces, as shown in the figure 2.

Figure 2: Ultrasonic image of a partially failed test coupon prior to separation showing a strong correlation between the ultrasound data and the observed interfacial failure.

The above image was captured in a matter of seconds with a portable ultrasound sensor without the need for gel couplants or immersion of the component in water [3].

Despite the wide range of industries that employ bonding technology and the multitude of material types that are bonded, there are a common set of issues faced by design and production personnel that can be addressed by ultrasonic NDT methods. These include questions of checking the adhesive material placement after bonding, confirming the bond dimensions (bead width, bondline thickness) and the requirement to detect potential defects such as large voids or porosity which could lead to adhesive or cohesive failure. Many of these issues were investigated in a recent European project concerning the use of adhesives bonding in shipbuilding [4].

An example of a typical bonding problem seen industry, figure 3 shows the variation in adhesive material placement within a bonded component. Of particular interest are the 'finger-print' patterns that have been created in the bondline due to compression and then subsequent relaxation of the adhesive joint prior to curing of the material.

Figure 3: Variation in adhesive bonding caused by compression and relaxation of the adhesive material during fabrication.
Conclusions
With the transfer of advanced imaging technology from medical to industrial applications, the prospects for ultrasonic inspection of bonded assemblies and advanced composite structures are exciting. This can be seen in the aerospace industry where the use of phased array imaging techniques are providing engineers with unprecedented, non-invasive images of the internal structure of complex composite components. This is leading to the prospect of employing ultrasonic technologies for both structural health monitoring and structural integrity assessment. Using current medical imaging rendering techniques, ultrasonic images of defects can be processed to provide 3D volume images of damaged components. By combining FE modelling, mechanical test data and advanced ultrasound NDT images, designers and stress engineers may be able to start predicting the effect of a production or in-service defect on the structural integrity of critical components.

References


Inspection of Adhesive bonding using Pulsed Thermography

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The technique of pulsed transient thermography involves using a short duration, high intensity flash of light to heat up the surface of a sample. The heat then defuses into the body of the sample. The sample's surface temperature is recorded by an infrared camera and computer system as it decays after this flash heating. The images showing the surface temperature are processed and the temperature decay profile for any point on the surface can be seen by looking these data. Subsurface defects produce anomalies in the surface cooling characteristics and are captured by an infrared camera.

Typically, the logarithmic time histories of the pixels in anomalous and sound regions of a sample have the profiles as depicted in Figure 1.

![Logarithmic Temperature - Time Histories of Pixels in Defective and Sound Regions](image)

This technique is gaining wide acceptance in the aerospace, automotive and power generation industries, owing to its non-contactive nature, speed of inspection, repeatability and sensitivity. One commercially available system is the ThermoScope developed by Thermal Wave Imaging Inc. (TWI) in the USA. This system consists of a central control unit, an imaging head and a complete suite of image acquisition and processing software as shown in Figure 2, below. The central control unit houses a PC, an intelligent system controller, a universal power controller and a flash power supplies. Its imaging head (shown in Figure 3, below) contains a flash heating system (power output from the lamp is 2kJ in 2 to 5ms) and a medium wave infrared camera (Merlin 3-5μm by Indigo), which uses a cooled indium antimonide detector with a frame rate of 60Hz and a focal plane array pixel format of 320(H)x256(V).

\[ \text{Detection related to } 121.\]
Pulsed thermography has been used for the detection and characterisation of Barely Visible Impact damage (BVID) and consequent disbonding in carbon composite (CFRP) panels, including aircraft skin and stringer structures as shown in Figure 4, below. In this figure, dark regions can be seen located diagonally across the image indicating cool regions. The cooling is produced by the presence of stringers adhesively bonded to the rear of the skin panel, which act as heat-sinks. A region of impact damage can be seen in the centre of the image (dark spot surrounded by lighter region). The impact damage has occurred on the edge of one of the stringers and this has caused the stringer to become disbonded, therefore producing a lighter (warmer region) surrounding it.
A number of adhesive-bond samples were manufactured using CFRP, steel and aluminium. These samples were bonded using araldite adhesive, with specific regions left adhesive-free to test their detectability. In Figure 5 and Figure 6 the red box overlayed on the images indicates a region of interest used to set image scaling parameters and should be ignored.

Figure 5 - CFRP with adhesively bonded aluminium and steel backing

Figure 5 shows a CFRP composite panel of 4mm thickness with two separate adhesively bonded backing plates made of 2mm thick aluminium and 2mm thick mild steel plate. The two backing plates were bonded along two edges (the top and bottom edges as seen in Figure 5). The warmer unbonded region can clearly be seen running laterally along the centre of the test piece, with the exception of the dark (cool) region that can be seen between the aluminium and steel plate locations. Although this region was not bonded, the cooling shown in the image shows that the plate is in close contact with the CFRP and is acting as a heat-sink. There is also a lighter (warmer) region on the top edge of the aluminium plate location which indicates that the aluminium has not bonded to the CFRP in this location. These two effects may have been caused by the aluminium plate not being completely flat.
Figure 6 shows a CFRP plate with a triangular CFRP plate bonded to the upper left hand corner. The bright spot to the right of the image is impact damage from a previous test. The darker (cooler) triangular region in the top left-hand corner of the image can clearly be seen, indicating the presence of the underlying CFRP plate. No adhesive was applied to the centre of the triangular backing plate (from top left-hand corner towards centre of the image). This can be seen in the difference in temperature of this region compared with the bonded edges. It should be noted that the unbonded region still produces a lower surface temperature than the regions with no backing material (e.g. bottom of image). This occurs as even though there is not direct contact, the thermal energy is able to propagate across the small air gap and into the backing material.