OBSERVATIONS IN THE STRUCTURAL RESPONSE OF ADHESIVE BONDLINE DEFECTS

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ABSTRACT

In terms of adhesively bonded repairs there are two main concerns with regard to structural integrity. These are the effect of debonds and weak bondlines on the load transfer and durability of the joint. The influence of load transfer depends on the stiffness of the bondline. When this is degraded the out-of-plane deformation of the joint will be modified locally. Observation of the out-of-plane deformation is a key in the identification of weakened bondline and represents an indication that either poor surface preparation or aging effects have occurred.

Holographic interferometry has been used to better understand the structural response of bondline defects, both debonds and weak bonds. The interferogram fringe patterns show the structural response and indicate whether the bondline has been broken or is weakly bonded. The significance of this observation is that weak bonds do affect the structural load response of the bondline in a number of ways. This effect is due to the reduction in bondline stiffness.

INTRODUCTION

Adhesively bonded joints as primary structural connecting methods can be a very efficient and light weight method of construction. There are various advantages of using adhesively bonded joining methods over conventional mechanically fastened joints. These include: few parts in the joint, full load transfer can readily be achieved, the joint is fatigue resilient, the method of construction also seals the joint, a stiffer connection is produced, the connection is light-weight, a smooth contour results, the action
of the adhesive provides corrosion resistance between the adherends, and no open hole stress concentrations are created.

However, the technology and construction method does have its disadvantages, such as: the adhesive can be subjected to environmental effects, the joint design is thickness limited, only shear loading is acceptable, the joint cannot be disassembled readily, and thermal residual stresses can be induced. The major concern with adhesively bonded joints in primary structures is that new design methods have had to be developed and are still being developed. This has required changes in engineering and trade skills to produce quality joints, particularly in the area of surface preparation. Surface preparation is the key to adhesively bonded joint quality and the primary problem is that it is difficult to inspect the bondline integrity.

This area of bondline integrity has been a significant ‘Achilles heel’ in the outright acceptance of adhesive bonding in aviation. Manufacturing processes have been refined to ensure joint quality. However, long term joint degradation can not be satisfactorily guaranteed following damage (i.e. impact or corrosion). The two questions to be asked are, ‘How can the quality of the bondline be assessed non-destructively after years in service?’ and, ‘Do the bondline properties change significantly with time?’. Currently available NDI techniques do not provide the answers.

This paper will review the defects that are a concern in adhesively bonded joints and what NDI techniques have been used to investigated and interrogate such defects. This is followed by a numerical study of how load transfer through a bonded joint is influenced by the mechanical properties of the adhesive. Then a discussion on the structural response and behaviour of adhesively bonded joints is outlined. Finally, a visual investigation using holographic interferometry is presented to better understand the structural load response of adhesively bonded joints with defects present.

**DEFINITION OF BONDLINE DEFECTS**

Defects in adhesively bonded joints can be generalised as either a debond or a weak bond\(^1\), Figure 1.
Figure 1: Generalised Defects in Adhesively Bonded Joints\textsuperscript{2}
**Debonds**

In adhesively bonded joints a debond is simply characterised and identified as a separation between the two adherends. As a result two traction free surfaces are created. The gross form of a debond is illustrated in Figure 1.a, however, other traction free microscopic forms of separation include voids, porosity and micro-cracking in the adhesive. During in-service operations, debonds are generally associated with moisture penetration at panel edges and bolt holes, bolt inserts in honeycomb panels, poor surface preparation, impact and/or local over-heating. Debonds are typically identified using common NDI methods, such as ultrasonic inspection and acoustic emission.

**Weak Bonds**

In complete contrast to a debond, weakly bonded joints show no sign of separation in the bondline. A weakly bonded joint is still effectively bonding the two adherends together. This is shown in Figure 1.b where there is a weakening of either the adhesive or the bondline interface. The bondline is defined in Figure 2. Currently available NDI methods can not reliably identify weak bonds due to the absence of traction free surfaces. The identification of weak bonds in joint production as a quality assurance measure is conducted through witness coupon destructive testing.

![Figure 2: Adhesively Bonded Joint Bondline](image)

**CURRENT METHODS OF NDI**

NDI techniques used in the quality assurance process for component manufacture and repair application of adhesively bonded structures occur in three areas:
a. defect or damage location;

b. defect or damage evaluation, i.e. type, size, shape and internal position of the defect; and

c. post-repair quality assurance.

The first and most important activity is to identify the location of the defect or damage. Assessment of the damage is firstly achieved by visual inspection, this is particularly true at aircraft operational levels. This assessment localises the defected or damaged area, and is then followed by a more sensitive NDI method. The more sensitive NDI method maps the extent of any internal defect or damage. Detailed NDI surveys are very important when dealing with adhesively bonded structures, particularly since the majority of the damage is usually hidden within the structure.

A major disadvantage of adhesively bonded joints is the difficulty in determining post-fabrication and through-life assessment of their structural integrity. As a result, an entire process quality control operation is set in place during the manufacture of adhesively bonded joints. Current NDI techniques are only capable of reliably detecting debonds and gross honeycomb core defects. Weak bonds are not successfully detectable with current commercially available NDI equipment. Noting that the weak bonds are associated with poor surface preparation, constituent material property degradation and/or an inadequate cure process, the quality control systems used in the aircraft industry for adhesively bonded joint manufacture at present are through:

a. certification of constituent materials (adherends and adhesives), certification and acceptance test, plus controlled storage conditions;

b. surface preparation equipment and process controls;

c. bonding fabrication and cure process controls;

d. complete assembly NDI; and

e. destructive testing of witness coupons.
The current in-service NDI techniques used in quality control and damage detection of adhesively bonded joints still have difficulty in correlating the NDI results with fracture or joint structural integrity. Also, the NDI of adhesively bonded joints must be addressed in two distinct areas. The first area is with the metal adherend joints and the second is the composite adherend joints. The main problem with current NDI techniques is that the materials being inspected have distinctly different phases at the macroscopic level, that is the adherend and the adhesive themselves. This makes defect or damage detection difficult, particularly with composite adherends.

A very brief discussion of the various NDI techniques associated with defect and damage location in adhesively bonded joints follows.

Visual

Apart from unaided visual inspection, which only identifies obvious defects, simple magnification can identify quite small surface defects. To improve defect or adhesive free edge crack visual clarity, enhancement with a dye penetrant can be used. Bondline free edge visual inspection will provide some assessment of the resin flow. The typical resin flows from a bonded joint edge are shown in Figure 3. The basic visual inspection method is inexpensive and simple, requiring low skill levels to perform, but it does need the surface to be clean and is only suitable for surface damage. The dye penetrant enhancement technique does however contaminate the surface to be inspected, so the component will require both pre-cleaning and post-cleaning.
Resin overaged or heat up too slow  
Poor fitting or lack of pressure  

c. Lack of Fillet  
d. Poor Flow  

Bubbles seen in fillet  
Fillet lifting from component  

e. Porosity  
f. Poor Adhesion  

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<tr>
<th>Figure 3: Adhesively Bonded Joint Edge Resin Flow Inspection</th>
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Another visually enhanced inspection technique is that used to check for leaks in sealed structures, like honeycomb/skin panels. The technique is known as the hot water leak test. However, after using the hot water leak test the component requires radiography inspection to disclose any trapped water.

**Impedance Method**

The impedance technique measures the response of the surface of a component to a low frequency vibration, and is good at detecting debonds. However, a couplant maybe required to ensure surface contact. The Fokker Bondtester (Figure 4) is a well known example of impedance NDI.
The implementation of ultrasonic inspection can range from inexpensive (≈$3,000) to quite costly ($150,000) in terms of the equipment required. The methods can simply provide details of depth and size of the damage, or full details of the topography of sub-surface defects. There are two principal techniques applied, pulse-echo (A-scan) or through transmission (C-scan), either is commonly used (B-scan is another ultrasonic scanning technique). Both A-scan and C-scan techniques measure changes in sound attenuation (amplitude or energy loss) of a reflected or transmitted sound wave. This energy loss is due to a mechanical vibration of the damaged region and thus the resulting changes in the attenuation of the transmission. Typical ultrasonic inspection techniques are shown in Figure 5.
Figure 5: Ultrasonic Inspection Techniques
The pulse-echo method displays amplitude of the return signal versus time and thus provides information on defect type, size, location and depth. It is reasonably sensitive, portable and recordable, but does require experienced operators, standard specimens and a coupling agent to transmit the sound energy. Having to use a coupling agent the component requires pre-cleaning and post-cleaning since the coupling agent is a source of contamination itself.

The through transmission method (immersion or water spray) is generally similar to the pulse-echo method, except that it is automated and therefore is faster, and provides full coverage of the component. The through transmission method does provide a more accurate definition of defect's size and location. The disadvantages of the through transmission method are that it requires double-sided access to the component, is for internal defects only, requires greater operator skill and uses relatively more expensive equipment. In all cases it is important to know the component geometry.

In adhesively bonded joints, thickness variations of the bondline adhesive can give 'false positives'. A 'false positive' is where the NDI technique indicated that a problem (typically a traction-free surface) existed, but in reality the bond is sound. Here, with adhesively bonded joints, variations in the adhesive thickness could result in a debond being suspected. This occurs due to the impedance attenuation variation between the adherend and adhesive over a very short distance (a few millimetres for the adherend and less than 0.2 mm for the adhesive).

The typical results of a pulse-echo scan of a composite skin and honeycomb core panel are shown in Figure 6. The ultrasonic results of Figure 6 indicate the following, A - front face of the composite skin, B - interface of the composite skin and the adhesive layer, C - back face of the adhesive layer which is bonded to the honeycomb core, D - a delamination in the composite skin (the exact depth of the delamination can easily be determined, and E - a debond between the composite skin and the adhesive layer.
Acoustic Emission

Acoustic emission techniques (Figure 7) are based on the operator or automated equipment detecting changes in sound from a light impact or elastic wave energy disturbances due to crack growth in the component. The component is generally loaded in some manner to initiate damage or grow existing damage. This loading produces the internal sound from the local adhesive fracture. These emitted sound waves are frequently termed stress waves. If the damage does not grow then it will not be detected. Detection of debonds in metallic adherend bonded joints is difficult due to the poor stress wave attenuation in the metal.

The various techniques range from a simple coin or hammer tap to automated acoustic emission techniques. The hammer tap technique uses a tapping device that lightly impacts the component's surface. The operator listens for changes in sound tone indicating variation in the elastic energy attenuation. The technique is simple to use and portable, but requires the operator to have a good ear and is only suitable to near surface (shallow) defects. It is also geometry dependent and very much operator subjective. The automated acoustic emission technique is sensitive to very small sound changes, it is portable and recordable, but requires experienced operators due to its complex output.
Acoustic/Sonic (Acoustic Transmission)

The acoustic transmission technique was developed from a combination of the ultrasonic and acoustic methods to study subtle defects in composite structures, in particular strength loss due to moisture absorption and fatigue. It has been used to determine the bondline strength of adhesively bonded joints. However, this and its indirect measurement of composite interlaminar shear strength are still under development. The technique requires an ultrasonic pulse be induced as a stress wave. This stress wave will produce acoustic emissions if, under stress, the material forms microcracks.

Microwave

Microwave NDI can be used mainly on non-metallic materials to determine the degree of moisture content through the measurement of microwave absorption. The technique requires two-sided access to the component and the shielding of metal parts. Operator safety is also essential and the component must
be cleaned prior to inspection. The application of microwave NDI techniques to adhesively bonded joints has had very limited success.

**Thermography**

Thermography is an NDI technique which measures the infrared radiation response of a structure. Thermal energy dissipation (infrared radiation) produces a thermograph. A thermograph is a series of isothermal contour lines which gives a surface temperature map, and this relates to the in-plane stress field. When defects are present in the form of traction free surfaces, then the rate at which thermal energy dissipates is reduced. The methods of applying the heat to the structure are: passive, which uses a heat gun, and active, resulting from vibration which produces internal friction at the damage site. The resulting heat pattern can be measured in real time with an infrared camera and computer system, Figure 8. These results are in a far-field form and can be related directly to the component stress state.

Thermography is most applicable to composite structures in the search of delaminations, voids, gross fibre fracture and concentration of matrix cracks. Little application to adhesively bonded joints has been attempted, but debonds, voids and inclusions could be detectable. Weak bonds may also be identified depending on the degree of load transfer degradation and the thermoelastic properties of the adhesive. The technique does provide an indication of the local stress state, but not necessarily under the normal load state conditions. Although the technique is portable and recordable, it is geometry dependent, needs experienced operators and assessors, and requires standards to verify results.

![Figure 8: Thermography Result of Composite Plate With a Hole (courtesy Reference 7)](image-url)
Interferometry

The use of light and its reflective properties to identify defects is the basis of interferometry. There are three basic techniques: Moiré, holography and shearography. Interferometric techniques provide a record of the defects, but are generally not portable. They are very sensitive techniques and show how the structure reacts under loading. However, they do require expensive equipment and need skilled operators and interpreters. Moiré interferometry is used to measure both in-plane and out-of-plane displacement (shadow Moiré), holographic interferometry measures purely out-of-plane displacement, and shearography measures the first derivative of the out-of-plane displacement, or the slope of the deformation. The difference between holographic interferometry and shearography is explained in Figure 9.

In all applications of interferometry the component under investigation is deformed under a representative load and the surface displacement can be measured up to an accuracy of 0.25 µm (depending on the laser light wavelength). The stress can be applied directly, or by either heat, vibration or pressure. A wide field of coverage can be obtained. Current methods of applying interferometry techniques require vibration isolation of the component to be inspected. This is the imposing limitation on the wide spread use of interferometry as a standard NDI technique. Shearography (Figure 10) has overcome this problem but the results can be difficult to visually interpret.

A defect in say a honeycomb core/thin skin panel is visualised by fringe pattern variations. In holographic interferometry and shearography the fringe patterns are illustrated in Figure 11.a and 11.b, respectively. Note the domed and double bulls-eye fringe patterns for holographic interferometry and shearography for a skin/core debond.
Leaky Lamb Wave

Obliquely orientated acoustic waves have shown a mode change at ply interfaces and adhesive bondlines. These modified acoustic waves travel parallel to the ply interface and bondline. Their properties are affected by the resin rich layer between plies and the adhesive layer properties. Delaminations and debonds have been easily identified as a result of interrogating the transmitted acoustic wave. Small changes in the adhesive properties (weak bonds) are not presently detectable in a reliable manner.
However, the kissing bond (delaminations or debonds that has intimate contact between the two free surfaces) can be reliably detected using this leaky lamb wave technique.

Figure 10: Shearography
(courtesy Reference 5)

Figure 11: Interference Fringe Patterns
LOAD TRANSFER INFLUENCES IN ADHESIVELY BONDED JOINTS

The elastic distribution of shear stress over the bondline of a double-lap joint is now recognised as being non-uniform, with peaked ends and a shallow trough, Figure 12. The distribution can be modelled as a hyperbolic function:

\[
\tau(x) = A \sinh(\lambda x) + B \cosh(\lambda x)
\]

Figure 12: Elastic Distribution of Shear Stress Along the Overlap Length

\[
\begin{align*}
E_o &= E_i = 10.3 \text{ msi} \\
t_i &= 0.125 \text{ ins} \\
t_o &= 0.0625 \text{ ins} \\
\tau_p &= 6 \text{ ksi} \\
\gamma_c &= 0.1 \\
G &= 60 \text{ ksi} \\
\eta &= 0.005
\end{align*}
\]
The shear stress distribution along the overlap length is determined from Equation 1, where \( A = 0 \) from boundary conditions:

\[
\tau(x) = \frac{\tau_{av}(\frac{l}{2})}{\sinh(\frac{\lambda l}{2})} \cosh(\frac{\lambda x}{2})
\]

for: \(-\frac{l}{2} \leq x \leq +\frac{l}{2}\) (2)

where: \( l \) = joint overlap length, see Figure 13

\( \lambda^2 = \frac{2G}{E_o \eta} \) (3)

\( E \) = adherend Young’s modulus

\( G \) = adhesive shear modulus

\( \tau_p \) = for the elastic/plastic shear stress/strain model

\( i \) = inner adherend

\( o \) = outer adherend

\( \tau_{av} \) = the average shear stress over the joint length

\[
\tau_{av} = \frac{P}{2l}
\]

\( P \) = the axial load per unit width

The effect on the elastic shear stress distribution with a variations in adhesive shear modulus can be shown through the following example. Given the representative data with Figure 13 for an elastically balanced, thermally matched double-lap joint, a plot of the shear stress distribution for an overlap length \( l \) of 4 inches (100 mm) and applied load/unit width \( P \) of 7,500 lb/in (1,313.5 kN/m), shows the classical stress distribution, Figure 14. This shear stress distribution is based on the adhesive elastic-plastic shear stress/strain model. The adhesive is a ductile type with shear modulus of 60 ksi (414 MPa). If the adhesive mechanical properties are reduced (i.e. shear modulus) the elastic stress distribution is modified by a significant reduction in peak stress at the overlap ends, but only marginal increase in the shear stresses over the central portion of the overlap length. This is clearly shown in Figure 14. Note, the average shear stress \( \tau_{av} \) and the areas under each of the curves remains the same.

The rate of change of the elastic shear stress distribution (or the rate of load transfer) is thus given as:

\[
\frac{\text{d}\tau}{\text{d}x} = \frac{\tau_{av}(\frac{l}{2})}{\sinh(\frac{\lambda l}{2})} \cosh(\frac{\lambda x}{2})
\]

for: \(-\frac{l}{2} \leq x \leq +\frac{l}{2}\)

Figure 13: Geometry and Nomenclature of the Double-Lap Joint
\[
\frac{\partial \tau(x)}{\partial x} = B \lambda \sinh(\lambda x) \tag{6}
\]

where:
\[
B = \frac{\tau_{av}(\frac{H}{2})}{\sinh(\frac{\lambda H}{2})} \tag{7}
\]

Figure 14: Variation in the Adhesive Stress Distribution with Changing Adhesive Stiffness
A comparative study for a double-lap adhesively bonded joint, using the same data as before, gives the shear stress rate of transfer over variations in adhesive shear modulus. This is shown in Figure 15. Thus, through a direct observation of Figure 15, we see that with a higher shear modulus the load transfer rate is significantly greater. Therefore, with a higher rate of load transfer there is a concentration of load at the joint end that induces problems. Such problems will ultimately lead to a failure at the joint end. However, stiffness losses in the adhesive do have an advantage, but a corresponding loss of strength will also be evident\textsuperscript{10}.

**STRUCTURAL BEHAVIOUR OF ADHESIVELY BONDED JOINTS**

The out-of-plane peeling effects in adhesively bonded joints are also influenced by adhesive properties as well as bondline properties. The transfer of load in a single-lap adhesively bonded joint will, by observation, induce out-of-plane bending, and thus peel stresses at the overlap ends, Figure 16. This out-of-plane bending and peel stress development is attributed to the load path eccentricity ($e$), Figure 16.a, and the attempt of the load path to align itself, Figure 16.b.

What is not so obvious is the development of local out-of-plane bending deformation and peel stresses in uniformly thick adherends of double-lap adhesively bonded joints. Although the overall load transfer is symmetric, the local load transfer at the overlap ends experiences a degree of eccentricity, resulting in peel deformation, Figure 17.
The development of the expression for the peel displacement and stress distribution assumes that the in-plane shear stress is uniform over the overlap end regions\(^9\). This is reasonable since the peel stresses are highly localised at the ends and become critical when in-plane shear stresses tend to be in the plastic region. Using the elastic-plastic shear stress/strain curve (Figure 18), when the shear stress/strain goes
plastic, the shear stress distribution over the joint bondline plateaus (Figure 19). Thus the in-plane shear stresses are essentially uniform at the overlap ends.

The expression for the peel displacement is given by Equation 8, and the general solution of Equation 8 is given by Equation 9:

$$\frac{d^4w_o}{dx^4} - 4\theta^4 w_o = 0$$  \hspace{1cm} (8)

$$w_o(x) = A\sin \theta x \cosh \theta x + B\cos \theta x \sinh \theta x + C\sin \theta x \sinh \theta x + F\cos \theta x \cosh \theta x$$  \hspace{1cm} (9)

where; \(x\) being defined from the centre of the bondline, Figure 20.

$$\theta^4 = \frac{E_c}{4D\eta}$$  \hspace{1cm} (10)

\(w_o(x)\) is the deformation of the outer adherend with coordinate location shown in Figure 20.
Figure 20: Geometry and Coordinate System for Adhesively Bonded Joint Peel Deformation

$\eta$ is the adhesive thickness.

$E'_c$ is the effective adhesive tensile modulus (see Equation 17)

$D$ is the flexural rigidity of the outer adherend.

$$D = \frac{E_o l_o^3}{12(1 - v_o^2)} \quad \text{for metallic adherends, and} \quad (11)$$

$$D = D_{11}^* \frac{l_o^3}{12} \quad \text{for composite adherends} \quad (12)$$

$D_{11}^*$ is the longitudinal flexural modulus of the composite adherend.

Based on boundary conditions at $x = \pm l/2$ and $x = 0$, and that the overlap length is sufficiently long ($l > 15t$, typically), the general solution coefficients are defined as:

$$C = F = 0 \quad (13)$$
Thus the approximate deformation of the outer adherend is given by Equation 15. Since the adherend through-the-thickness stiffness is much greater than that of the adhesive, the deformation of the outer adherend matches that of the adhesive bondline. The maximum deformation will occur when $x = \pm l/2$, giving:

$$w_o(x) = -\frac{\pi\nu}{2D} \sin \left( \frac{\varphi l}{2} \right) \sin \varphi x \cosh \varphi x + \frac{\pi\nu}{2D} \cos \left( \frac{\varphi l}{2} \right) \cos \varphi x \sinh \varphi x$$

Assuming that the peel stress is elastic to failure (a reasonable assumption for most engineering structural adhesives), then the peel stress distribution is given by:

$$\sigma_c(x) = \frac{E_c w_o(x)}{\eta}$$

The effective tensile through-the-thickness modulus of the adhesive bondline is essentially governed by the adhesive tensile modulus (in a constrained boundary). However, because the inner and outer adherends are both elastic, a proportion of their structure, attached to the adhesive, will also deform. The deforming mechanism is thus represented by three springs in series, Figure 21.
The relationship of the effective tensile (through-the-thickness) modulus of the bondline is thus:

\[ E'_c = \left[ \frac{1}{k_1 \frac{E_c}{E_i} + k_2 \frac{E_c}{E_o}} \right]^{-1} \] (17)

where: \( E_c \) is the constrained tensile modulus of the adhesive (the modulus is constrained because the adhesive is very thin between adherends and these adherends restrict the lateral contraction of the adhesive).

\( E_i \) and \( E_o \) are the Young moduli of the inner and outer adherends.

\( k_1 \) and \( k_2 \) represent the proportions of the inner and outer adherends under-going out-of-plane deformation. Through experimental observation\(^{11} \) \( k_1 = 4 \) and \( k_2 = 2 \), respectively.

The representative peeling displacement and associated peel stress distributions are illustrated by the following typical data and produce Figures 22 and 23, respectively. Observation of Figure 23 clearly shows that the maximum peeling effect occurs at the overlap ends, within 5% of the overlap length, or approximately the thickness of the outer adherend.

Adhesive plastic shear strength \( \tau_p = 6 \text{ ksi} \) (41.4 MPa)
Adhesive thickness \( \eta = 0.005" \) (0.125 mm)
Adhesive Tensile Modulus \( E_c = 500 \text{ ksi} \) (3.5 GPa)
Outer adherend modulus \( E_o = E_i = 10.3 \text{ msi} \) (71 GPa)
Poisson's ratio \( \nu_o = 1/3 \)
Outer adherend thickness \( t_o = 1/16" \) (1.59 mm)
Overlap length \( l = 4" \) (100 mm)
Bondline weaknesses in peel show effective changes in the peel distribution. Two effects are demonstrated. The first is a change in adhesive tensile modulus ($E_c$) and the second a reduction in in-plane maximum shear strength ($\tau_p$). Reviewing the expression for stress distribution, Equation 16, any variation in $E_c$ will modify $\sigma_c(x)$ directly and through changes in $w_o$ (a function of constants $A$ and $B$,
and parameter $\theta$, each of which is proportional to $E_c$ in some manner, Equations 14, 15 and 10). By reducing the value of $E_c$ in the illustrative example from 500 ksi to 250 ksi by 50 ksi increments the resulting peeling deformation and peel stress distribution is shown in Figures 24 and 25, respectively.

![Figure 24: Peeling Deformation Distribution Variation](image)

With a variation in the in-plane plastic shear strength ($\tau_p$) the effect on peel displacement and peel stress is illustrated in Figures 26 and 27, respectively. The illustrative representation of the in-plane shear stress/strain behaviour is shown in Figure 28.a. The in-plane mechanical properties being viscoelastic in behaviour, Figure 28. A similar behaviour is seen for the out-of-plane mechanical properties, Figure 28.b. Although the adhesive is essentially isotropic, the out-of-plane behaviour is near linear elastic to failure. This out-of-plane or constrained tensile stress/strain behaviour is significantly influenced by the adherend boundary. The boundary conditions effectively constrain the adhesive lateral contractions, as illustrated in Figure 29.
Figure 25: Peel Stress Distribution Variation

Figure 26: Peeling Deformation Distribution Variation
Figure 27: Peel Stress Distribution Variation

Figure 28: Shear and Tensile Stress/Strain Behaviour with Degradation

a. Shear Stress/Strain Behaviour (In-Plane)
b. Tensile Stress/Strain Behaviour (Out-of-Plane)
For both a reduction in adhesive shear modulus and in-plane shear strength the peak peel stresses are reduced. This was clearly evident when ductile and brittle type adhesives are compared. Ductile (lower modulus) adhesives have reduced peel stresses. However, as illustrated in Figure 24, peel deformation ($w_o$) is increased with a reduction in constrained adhesive tensile modulus.

FINDING WEAK BONDS

Weak bondlines, by definition, are where either the adhesive or bondline interface has been poorly cured or contaminated, respectively, and thus the mechanical properties have been reduced. However, the bondline is still in contact or stuck. As such the inspection of bondline weaknesses is very difficult. Standard NDI methods, such as ultrasonic, are ineffective in the identification of weak bondlines.

The effect on mechanical properties due to weakened bondlines is a reduction of the interface or adhesive shear and peel stiffness. When an adhesively bonded joint is under load, all areas of the joint will experience the same level of strain, but as shown in Figure 30 the stress level will be different.
The impact of bondline weakness on load transfer is considered as a symmetric or asymmetric weakness. With a symmetric bondline weakness there would be a reduction in both the in-plane and out-of-plane stiffness of the entire bondline. Using the same analogy as in Figure 21, this reduction can be simply represented by the following expression\(^\text{12}\), with the bondline peel stiffness \((k_b)\) given as:

\[
\frac{1}{k_b} = \frac{1}{k_{\text{int}}} + \frac{1}{k_a} + \frac{1}{k_{\text{int}}} \tag{18}
\]

where:

\(k_{\text{int}}\) = The bondline interface stiffness  
\(k_a\) = The adhesive effective through-the-thickness stiffness

Therefore, for a good interface on both surfaces:

\[
k_b = \frac{k_a k_{\text{int}}}{2k_a + k_{\text{int}}} \tag{19}
\]
as \( k_{\text{int}} \rightarrow \infty, \quad k_b \rightarrow k_a \), current representation of the bondline stiffness, and

if \( k_{\text{int}} \rightarrow 0, \quad k_b \rightarrow 0 \), i.e. a debond.

A plot of the bondline stiffness \( (k_b) \) versus that of the adhesive stiffness \( (k_a) \) is shown in Figure 31. Figure 31 clearly shows that with any degradation to the interface the bondline stiffness (i.e. the interfacial stiffness properties approach that of the adhesive) is also reduced. Furthermore, the bondline stiffness is effectively that of the adhesive with the understanding that the interface stiffness is much greater than that of the adhesive stiffness.

![Figure 31: Bondline Stiffness vs. Interface Stiffness](image-url)
f the bondline weakness is only on one side of a double lap joint then an asymmetric condition is apparent. Referring to Figure 30, as the strain in the joint increases, it does so with uniformity across the joint thickness. As a result the stress being transferred through each outer adherend will be different. This means that the good bondline will attract more load. In terms of peel deformation, greater peeling will occur on the good bondline. This was investigated with PHITS (Portable Holographic Interferometry Testing System), looked at the effect on peel deformation of a double lap adhesively bonded joint with one of the outer adherend surfaces improperly prepared prior to bonding. The experimental set-up for capturing the interferograms on both sides of the specimen is shown in Figure 32. The holographic plates were exposed simultaneously by a reflective technique illustrated in Figure 33.
The results of this holographic interferometry investigation are shown in Figure 34. Clearly the peeling deformation is less on the weakened side when compared with the uncontaminated side of the joint. For bondline with a high degree of stiffness, a sharp peel deformation adjacent to the free end of the lap is expected. This is identified by the closeness of the fringes near the edge of the lap in the lower interferogram of Figure 35.
Figure 35: Peel deformation of the lap joint shown in Figure 34 measured from the holographic interferograms.

Figure 35 shows the deformation of the lap joint measured directly from the holograms of Figure 34. The steep deformation of the good bond near the edge of the lap is evident when compared to the deformation of the lap on the poorly bonded side. These higher out-of-plane deformations are a direct result of both the weakened mechanical properties (in particular the out-of-plane stiffness) of the contaminated side of the joint and the greater load being transferred through the good side of the joint.

During an investigation of out-of-plane deformation of internal and free edge debonds, several of the specimens exhibited unusual and unexpected fringe patterns. These fringe patterns were suspected to be weak bondlines. The specimens were prepared in the following manner:

a. The lay-up of the specimens, Figure 36, included release agent being strayed onto the induced debond region and two strips of Teflon film.

b. The curing processes followed the recommended manufactures guidelines for HYSOL EA9628.06C film adhesive, and was achieved with a vacuum bag and heater blanket technique.
The initial holographic interferogram of the first specimen tested (a 30 mm radius semi-circular free edge debond) produced Figure 37 at an pre-load of 47.7 kN and an incremental load of 12.1 kN. At first the result appeared acceptable, but there was much concern that a 12.1 kN load increment was required to produce out-of-plane displacements in a 3 mm thin sheet. Holographic interferometry investigation of the 15 mm radius semi-circular free edge debond on the other free edge of the specimen produced the interferogram of Figure 38 with an incremental load of 11.7 kN. Again much concern was raised that the defect was not separated and was in fact still adhering. A tap test survey revealed this to be so.
In both of the interferogram, Figures 37 and 38, there is fringe pattern anomalies due to the presence of the defect. These changes in the fringe pattern are a direct result of through-the-thickness property changes in the bondline interface. After the debonded region was opened up, the fringe patterns that were observed are shown in Figures 39 and 40.

In Figure 37, the incremental load is one tenth of that which produced the fringe pattern of Figure 37. With the load increment the same, the fringe pattern and fringe density of Figure 40 is vastly different from that of Figure 38.

A review of other defect variant fringe patterns for the through-the-thickness rectangular debond is shown in Figures 41 and 42. Prior to physical opening of the debond, the interference fringe pattern of the left hand side of the specimen produces Figure 41, with an initial load of 27.1 kN and an incremental
load of 0.5 kN. With the left portion of the debond opened, the fringe pattern is shown in Figure 42. Note that the incremental load in increased by a factor of four.
The difference in the fringe patterns is obvious. On the right hand side of the interferograms the fringe density has increased by near the same factor of the incremental load increase. However, we the debond has been opened the fringe density in Figure 41 has been increased well above that of Figure 42. Similar effects were observed in the internal circular and square debonds. Figure 43 are the before and after debond opening for the internal circular defect, and Figure 44 for the internal square debond.
In both case of the internal debonds the increase in fringe density of the after debond opening was produced at a much lower incremental load. With the debond opened, the fringe pattern is a regular shape and clearly defined. Weakened bondlines produce very irregular fringe patterns as clearly seen in the before shot of both internal debonds. However, the weakness can still be seen in the fringe pattern. There appears to be a few characteristics of the fringe pattern that can be used to identify weak bondlines. These are:

a. a global irregularity in the fringe pattern,

b. a high incremental load to obtain significant fringe anomalies,

c. a non-doming fringe pattern shape, and

d. limited influence on the global fringe pattern.

Figure 43: Holographic Interferograms of the Internal Induced Circular Debond
CONCLUSION

Adhesively bonded joints have many advantages over other structural joining methods, particularly in their efficient load transfer in thin components and structural repairs. However, the general application of adhesively bonded joints has suffered due to their difficulty to inspect bondline quality following manufacture and in-service life. The major concern is degradation of the bondline mechanical properties due to either poor surface preparation or improper curing conditions.

The weak bondline problem will have a significant and measurable effect on the load transfer capability of the joint. Using the elastic-plastic shear stress/strain behaviour of Hart-Smith, this paper has shown that a variation in the shear stiffness of the adhesive has a corresponding change in the peak stresses during load transfer and modifies the rate of load transfer across the over-lap length. This in itself has some benefits in improving the load carrying capacity, but is more like to adversely affect the joint’s mechanical performance.
The second influence in joint load transfer capacity is the reduction in peel strength and stiffness. The weak bondline will cause premature failure of the joint free edge due a loss of peel strength. A corresponding loss of peel stiffness does reduce the out-of-plane deformation of the joint free edge, but is load magnitude effected. However, there is a modification to the put-of-plane deformation performance and this is the key in identifying the defective region.

Holographic interferometry has been shown to successfully identify regions of weakened bondlines. The fringe pattern variation is easily observed over a defective bondline region. Also, when compared to a pure debonded region, the load required to produce weak bond fringe pattern variations is significantly different. PHITS is a practical and relatively simple method in the identification of bondline defects. It has also successfully been applied in the identification and characterization of other structural defects, including: composite delaminations, structural heat damage, mixed mode fracture mechanics, mechanically fastened joint multi-site damage, and fastener stiffness problems.

REFERENCES


