Characterisation of Bond Line Porosity

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The purpose of this thesis project was to investigate the relationship between the porosity present in a bond line and the strength of the bond to contribute to the writing of an industry standard. This relationship was investigated using ASTM D3762 Boeing Wedge Test conducted in an artificial ageing environment of 50°C and 100% relative humidity (RH) to accelerate the rate of crack propagation. Testing was conducted on samples prepared under ideal conditions to establish a reference for subsequent testing on samples with porosity induced by means of carbon fibre tow leak paths into a vacuum bag. The rates of crack propagation between the samples were compared and a relationship was observed between porosity and crack propagation. Photographic analysis of the porosity present in the samples was conducted using Matlab to confirm the exact level of porosity which showed the expected difference between ideal samples and those prepared with induced porosity. Investigation was conducted into potential for non-destructive evaluation (NDE) of bond line porosity, however actual NDE was not conducted in his project.

Nomenclature

B = Coupon width
Cr = Crack Length
ΔCr = Change in Crack Length
AVG ΔCr = Average Change in Crack Length
ΣAVGΔCr = Cumulative Average Crack Propagation
E = Young’s Modulus
h = Perpendicular distance from arc tangent midpoint to arc
H = Coupon height
I = Second moment of inertia
L = Pixel Luminance
α = Proportion of section still in elastic range after initial yielding
ν = Poisson’s Ratio
σY = Yield Stress
w = Arc Tangent Length

1 Lieutenant, School of Engineering & Information Technology, ZEIT4500.
I. Introduction

Composite materials are of increasing importance in engineering fields since they offer tantalisingly improved properties when compared to a homogenous material. This is a result of the co-operation between two materials where the most advantageous aspects of each materials mechanical properties work in concert to minimise the deficiencies. A simple example of this is reinforced concrete where steel effectively carries the tensile load and the concrete the compressive load. Composite materials are particularly advantageous where their increased mechanical properties can lower the weight of the material required and increase overall efficiency; this is of particular importance in the aerospace industry where composite materials are playing an increasing role.

The problem with composite materials lies in the means of bonding the component parts together into a single element. Traditional means of fastening such as bolting and riveting are ineffective primarily since they induce local stress concentrations at the point of fastening which causes local failure at loads below which a global failure would occur. As such, these methods of fastening do not make best use of the composite materials properties.

A practical solution can be found in adhesive bonding which, when applied correctly, will effectively distribute an applied load over the entire area of the bond making best use of the entire composite material. Adhesively bonded materials do have an inherent flaw, being porosity, which lowers the overall strength of the bond and as such the composite material. Porosity however, is inherently difficult to determine once the bond has been made for three main reasons. Firstly that the bond cannot be disassembled and reassembled without destruction, secondly visual inspection is precluded since the bonded materials are generally not transparent and finally porosity is comprised of very small pockets of air which would not be easily visible anyway. From this it can be seen that an effective non-destructive method of determining bond line porosity is required for industry analysis of components and secondly that a standard for acceptable porosity must be established for reference.

II. Background

A. Uses of Structural Adhesives

Structural adhesives have found applications in a plethora of engineering fields, in particular aerospace, civil and mechanical engineering. This trend has existed from ancient times and is set to expand in the modern era with increasing use of composite materialsii. Examples of adhesive use in these industries include sandwich panels in aircraftiii and the construction of metal wall panels in constructioniv. Adhesives are finding use in these areas because they offer certain advantages over conventional mechanical fasteners which have otherwise been the norm.

These advantages include continuous contact between adhered surfaces which exclude contaminants and increased the bond area resulting in a larger stress distribution. Conversely a mechanical fastener such as a bolt or rivet only creates contact at this immediate location which results in a localised stress concentration. Additionally adhesive joints which retain their ductility have a greater resistance to fatigue then rigid mechanical connections. Indeed, joints made from adhesive are generally lighter than those mechanically fastened which is a particular advantage when efficiency in design is a requirement.

Notwithstanding these advantages adhesive joints have a critical drawback which is the crux of this project: the in-situ bond strength is extremely difficult to determine through non-destructive meansv which is required when the bond must be relied upon structurally.

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B. Porosity

According to Cawley three types of defects are encountered in adhesively bonded joints, complete disbonds, voids and porosity, poor cohesive strength of the adhesive layer and poor adhesive-adherend interfacial properties\(^{\text{vi}}\). Of these three the latter two can generally be prevented selecting an appropriate adhesive\(^{\text{vii}}\) and through adequate surface preparation\(^{\text{viii}}\). Disbonds and voids can again be minimised through careful surface preparation and bonding procedures. Porosity however, as a rule will exist to some extent in all bond lines regardless of the preparation or process used to create the bond.

Within the bond line itself porosity exists as volumes absent of the adhesive, similar to voids but generally smaller in size\(^{\text{ix}}\). They occur as a result of volatiles or gasses present in the bond line during curing. Significant formation of voids can also occur if surfaces are not adequately dried post surface preparation before bonding. This is caused by the vaporisation of liquid present on the bond surface during heat curing. In their study, Chew, et al identified porosity of this type to be particularly vulnerable to `vapour pressure failure’ at high temperatures, since the water vapour in the pores would expand under heat to the point where it could exceed the failure stress of the adhesive\(^{\text{x}}\).

In addition to the mode of vapour pressure failure described by Cheng, uniform porosity in a bond line decreases the shear and peel capacities of the bond. This is elementary since porosity causes a decrease in cross-sectional area which in turn increases the applied stress potentially causing unzipping failure, however the exact magnitude of the decrease is not so trivial. This is a result of the random and fine nature of the bubbles that make up the porosity since it is impossible to identify the discrete cross-section with maximum porosity and use this as the effective strength of the bond. It is more effective to use a per cent measure of porosity present as the criteria for determining if a bond line is acceptable for use.

It has been shown that shear stresses in a bonded joint peak at the bond line edges and are almost negligible in the centre of the bond, this distribution is shown in Figure 1 taken from Hart-Smith’s paper Aerospace\(^{\text{xi}}\). From this it can be seen that the edges of a bonded joint would be the most adverse location for flaws in a joint and porosity is no exception. In this case however, uniform porosity is preferable over the entire bond as opposed to a localised concentration of porosity near an edge of a bond line. This is because, as discussed above porosity will lower capacity but if a uniform distribution exists the expected stress distribution can develop as shown in Figure 1. If porosity occurs as a localised group near the edge of a bond the lower capacity causes an increase in the stress carried by the areas adjacent to it. This can cause higher peaks then would otherwise occur inducing the phenomenon where an adhered joint would fail at an applied load less than that expected. In this instance, porosity has caused the failure of a sound portion of adhesive without failing itself.

Since porosity will be present in all bond lines it is interesting that a definitive standard for allowable porosity does not exist, indeed it is left to the manufacturer to determine their own acceptable level of porosity for their products\(^{\text{xii}}\). This notable absence of an industry standard leads manufacturers to be conservative in their application of individual standards of acceptable porosity since they alone would carry the responsibility for

\(^{\text{vi}}\) Ibid.
their product without the assurance of having complied with a standard. This can lead to potentially satisfactory bonded components being discarded unnecessarily, a wasteful practice which could be ended with the identification of an acceptable level of identifiable porosity to be implemented as an industry standard which is the aim of this project.

C. Non-Destructive Evaluation Methods

As has been previously mentioned, a significant challenge to the introduction of an industry standard for allowable porosity is the ability of manufacturers to accurately determine the porosity present in their products. Of course this property can be determined relatively easily by destructive testing, using Coggin’s method of dye penetrant analysis for example; however destructive testing defeats the purpose of manufacture. According to Rose, it is this inability to accurately determine the quality of a bonded joint which has minimised the use of structural adhesives in safety critical areasxiii.

The advantages of adhesive bonding over traditional mechanical fasteners have already been discussed and in light of these advantages it makes sense to remove the barriers to the employment of adhesive bonding in safety critical roles. So far the most promising prospect for NDE of bonded joints is in the realm of ultrasonics, although other non-destructive methods have been explored including liquid penetrant tests radiography and transient thermographyxiv. Of these methods some can be discounted for the purpose of detection of voids. Liquid penetrant tests would only highlight the voids exposed to penetration, such as those occurring on a finished surface as is the case with Coggin’s method. In reality this would only show the in situ porosity at the edge of a bond line since interior porosity is effectively sealed.

Transient thermography works in a manner similar to ultrasonics in that this method measures the response of a material to a wave action. In the case of thermography the wave is applied in the form of a thermal pulse which acts as a wavefront through the material allowing comparative measurements in temperature to be taken on either face of the material and compared to the expected thermal propertiesxv. With the use of thermal imaging cameras areas of high porosity could theoretically be seen as cooler areas on the surface of the material since the bubbles of the porosity will serve as barriers to thermal transmissionxvi. Limitations to this method can be found in the nature of porosity itself since it generally occurs as a dispersed field of bubbles which are small in size. This may lead to a uniform appearance under thermal imaging as opposed to ‘patches’ appearing which would more likely indicate a void or disbond. Transient thermography for rapid scanning of large bond areas can however induce a prohibitive cost in machinery.

Ultrasonics as an inspection method works by initiating a series of ultrasonic sound (pressure) waves with a transducer which are carried to the tested specimen via a coupler, usually a fluid. The reflections of the waves are noted and the time interval of their echo is compared to the wave velocity of the specimen to determine the location and magnitude of a defect. The distortion can be compared to the expected norm to locate defects in a material. It has already proved very effective in non-destructive evaluation of bond lines in locating voids and disbondsxvii. This fact is encouraging however it shows that ultrasonics will require some refinement in order to determine porosity which consists of smaller bubbles then voids. Rose also mentions that frequencies in the 30 MHz range show particular promisexviii, so this would be an ideal starting point for laboratory tests. Indeed higher resolution results are achieved with higher frequencies which would be a requirement for analysing porosity in a bond line.

D. Selection of Materials

The materials for this project were primarily selected to maintain continuity with the work conducted in previous years. Specifically this included the Cytec FM300 film adhesive which was used by McMullan in 2010xix which was suitable for inducing porosity using the carbon fibre tow method. This adhesive is also easily

xiv Ibid.
xviii Ibid.
stored in a freezer for prolonged periods and is simple to apply since it comes as a film on a carrier cloth. This simplicity in application, especially when compared to two-part resins gives increased consistency between samples since one batch of film adhesive could be used throughout the tests, as opposed to being mixed each time.

Aluminium was chosen as the adherend due to its homogenous nature and well known materials properties. These consistent properties meant that failure of the adherend could be discounted during testing. When it was planned to conduct ultrasonic testing, a homogenous material such as aluminium would provide consistent attenuation to the ultrasonic waves whereas a composite adherend would have a significantly more complex attenuation process.

III. Procedures

A. Coupon Preparation

Coupons were prepared in the ADFA Composites Laboratory using 3.2mm aluminium pre-cut coupons of dimensions 25 mm x 150 mm.

1. Removal of Free Radicals: The face to be bonded of each coupon was wiped with acetone on a ‘kim-wipe’ and allowed to dry.
2. Surface Abrasion: Each coupon was abraded with a ‘scotch-brite’ pad with distilled water as a lubricant. This was done five times in the major axis direction and five times in the minor axis direction. This ensured that deep scratches were not created in a single direction and a uniform surface preparation was achieved.
3. Wipe Clean: Each coupon was wiped five times with distilled water and a kim-wipe to ensure complete removal of abraded particles from the adherend surface.
4. Cylane Application: Solution of 1:100 Cylane in distilled water was applied to the surface and agitated for 15 minutes.
5. Adhesive Application: Coupons of Cytec FM300 Film adhesive were cut to size with a crack starter consisting of an application of release film in one end were positioned between the aluminium panels.
6. Curing: The prepared samples were thermally cured in a vacuum bag to minimise porosity. The thermal cure was up to 250 °C as shown in Figure 2. Thermocouple applied to samples to regulate temperature.

Induced Porosity Coupons

1. Steps 1 – 5 are identical.
2. Leak Paths: Carbon Fibre Tows of 6000 fibres were spread to 25mm at one end of the tow width and the spread end inserted into the coupon at the opposite end of the crack starter film.
3. Curing: Thermal cycle is identical. Vacuum bag is set to desired pressure (40 Psi or 70 Psi) with carbon fibre tow leak paths protruding from the sealed edges to allow air ingress as shown in Figure 3.
B. ASTM D3762 Wedge Test
1. Surface Preparation: Each cured coupon was finished on one surface with 300 grit sandpaper to remove excess adhesive and give a uniform surface for observing crack propagation.
2. ASTM D3762 conducted in accordance with ASTM directions at Standard Test Environment #7 (50°C and 100% RH).
3. Initial crack length recorded and crack propagation recorded hourly using a microscope with 0.1 mm graduations.
4. Test conducted for minimum of 5 hours.
5. Samples forced apart at conclusion of test to confirm failure mode.

C. Photographic Porosity Analysis
1. Preparation: Split samples were thoroughly washed under running water and the area under the crack starting film lightly abraded with 600 grit sandpaper in order to expose voids just below the surface.
2. Dye Penetrant Application: ARDROX 907PB Red Dye penetrant was applied to the coupons and allowed to sit for 30 minutes to allow adequate penetration.
3. Samples were washed under running water as per manufacturer’s directions and allowed to dry.
4. ARDROX 9DIB Non-aqueous Developer was applied with excess developer removed with a damp cloth.
5. Photographs were taken through the same microscope used in ASTM D3762 with a 14 megapixel camera for Matlab analysis.
6. Segments of photographs of each sample were analysed using Matlab to count the per cent occurrence of a selected reference pixel based on luminance exclusion.

IV. Results

A. ASTM D3762 Baseline Tables

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C. Confirmation of Baseline

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D. Matlab Porosity Analysis

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V. Discussion

A. Baseline Testing and Confirmation

On their own, few inferences can be drawn from the initial baseline testing. The baseline testing was the first attempt at coupon manufacture in the project so it was useful to conduct a number of tests to confirm the process and the accuracy of the results.

Of the three sets of coupons prepared for the baseline testing the second set failed under the elevated thermal conditions in the environmental chamber. It was suspected that this set of coupons may not have performed as the previous set had due to a malfunction of the thermocouple during the curing process. This resulted in an incorrect temperature profile during the cure and post cure the adhesive was able to be indented with a fingernail. When placed in the environmental chamber at 50°C the adhesive did not exhibit brittle crack propagation, however the adhesive reverted to the state of a viscous fluid and the two panels delaminated. Whilst this test was considered a failure it was important in highlighting the requirement for a correct curing cycle in order to maintain the strength properties of the adhesive.

The two successful sets of coupons for the baseline testing indicated reasonably similar results which showed that a consistent process was followed. One anomalous result was observed in the third set of coupons where a crack propagation of 2.5mm was observed over a single hour. This was significantly larger than the observed propagation for any other one hour period in any other test and had the effect of skewing the ASTM D3762 result for the third set of coupons to an excessive propagation rate. It is highly probable that this anomalous result was caused by an error in measurement during the conduct of the test. When this apparently anomalous result was removed the propagation was comparable to the other baseline coupon set.

B. Induced Porosity Testing

Induced porosity coupons were prepared at vacuum bag pressures of 40 PSI and 70 PSI and tested using ASTM D3762 methods as per the baseline testing coupons, these two pressures being the lower and upper limits used by McMullan respectively.

As shown in Tables 3 and 4, it was observed that crack propagation ceased to occur after two hours even when left for extended periods, with one minor exception. This contrasted to the initial baseline testing where crack propagation occurred out to five hours, thus a confirmation of the baseline results was undertaken with another sample prepared with no leak paths. This sample showed no crack propagation after two hours but yielded similar cumulative average crack propagation to the earlier baseline tests so it was deemed that a
baseline had been achieved. The plotted results of the induced porosity testing against the baseline testing are shown below in Plot 1 below.

Plot 1: ASTM D3762 Results

From Plot 1, it can be seen that the 2.5mm crack propagation observed after two hours on Coupon 2 in the No Leak Paths – Baseline 1 test are most likely an anomalous result since this measurement drives the plot far higher than other baseline tests. A more likely result can be determined by discarding this result and adjusting the averages for the plot accordingly; this is shown below in Plot 2. The Baseline 1 curve now conforms much more closely to the other baseline results.

Plot 2: ASTM D3762 Results with anomalous result removed
The initial gradients in Plot 2 show the period of observed crack propagation during the first few hours of the ASTM D3762 tests with the plateau showing the cessation of crack propagation. This plateau indicates that none of the coupons failed outright in the test, however the difference in gradients illustrates the differing crack propagation rates between the ideal and induced porosity samples. As expected the 70 PSI sample displayed a significantly higher rate of crack propagation commensurate with its expected porosity which was confirmed by Matlab analysis discussed below. It was interesting to note that the 40 PSI sample showed similar crack propagation to the ideal samples which shows that the lower range of porosity is less adverse to bond line strength that higher ranges. The relationship between observed crack propagation and porosity is shown below in Plot 3.

This plot shows that the effect of porosity on crack propagation is less between the expected minimum of ≈0.5% and the porosity induced in the 40 PSI coupons of ≈1.2% when compared to the effect of porosity beyond 1.2%. With three data points the relationship can only reasonably be displayed as linear, however it is expected that with more data points that the plot will display a curve with the point of inflection between 1.2% and 3.7%. This point of inflection would identify the level of acceptable porosity in adhesive joints since the rate of crack propagation is directly related to bond strength.

C. Matlab Porosity Analysis

The induced porosity coupons required photographic analysis to confirm the exact porosity present in the samples. This is because the method for inducing porosity has not yet been refined to an exact science due to the few tests conducted to date. Whilst an inference can be made to the expected level of porosity from McMullan’s previous work\textsuperscript{xxi}, an exact measurement of porosity is required for comparison. In the initial thesis planning, it was expected to utilise Matlab code

\textsuperscript{xxi}McMullan, R. “Characterisation of Bond Line Porosity”, Journal of Undergraduate (Unpublished) UNSW@ADFA, ACT 2010.

![Figure 4: Porosity analysis photograph](image)
developed by Coggin, however this was not available, so code was developed independently.

In the photographs of the samples it was evident that the developer had accumulated in the pits left by porosity and had turned white as shown in Figure 4. Essentially this meant that the pixels in the photograph showing porosity were brighter than the others which were a means of isolating the porosity in the photograph. In developing the Matlab porosity analysis code it was first planned to develop a code to count the occurrence of a certain colour pixel represented by its Red-Green-Blue (RGB) value, however this would result in only exact matches being counted. This method would not give an accurate representation of porosity since each apparently ‘white’ spot is actually made up of several different pixel shades. A more useful method of analysis was determined to be converting the image into a binary black and white (BW) image and counting the occurrence of white pixels.

This was achieved in Matlab by using the inbuilt function `imread` to convert the colour image into an array of its pixel RGB values with their Cartesian location. A reference pixel was selected using the `imtool` function which produced the image in the Matlab workspace and returned the RGB values of a pixel when the cursor was placed over it. The luminance of the pixel in the RGB colour space was determined using the formula:

\[
L = \frac{(0.299R + 0.587G + 0.114B)}{255}
\]

Where R, G and B correspond to the pixel values of red, Green and blue in the RGB colour space within the limits of [0, 255]. The purpose of dividing through by 255 is to provide a value of luminance within the limits [0, 1] required as a parameter for the Matlab function `im2bw`. This function converts the true colour image read by `imread` into a binary BW image with the luminance of the reference pixel as the threshold between conversion to either black or white. This is to say that pixels of equal or greater luminance then the reference pixel will be shown as white in the BW image and vice versa.

A 5% bracket of luminance was taken about the reference pixel in order to account for the variability of pixels in a patch of colour which is apparently homogenous. This was done by determining the count of white pixels from the lower luminance threshold and subtracting from this the values from the upper luminance threshold. This allowed a value for a 5% band of luminance to be taken which accounted for the possibility that the porosity reference pixel was not the most luminous pixel in the frame. A per cent value for porosity was taken simply as a proportion of white pixels to total pixels.

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*Plot 4: Porosity Distribution vs Vacuum bag pressure*

xxii MathWorks, Matlab V7.11.0.584 (R2010b), 2010.
xxiii Ibid.
xxiv Ibid.
The results of the porosity analysis give an expected result when considered in the context of the ASTM D3762 results to the point that the 70 Psi coupons were expected to have greater porosity due to their manufacture process and their strength results.

The very tight grouping of porosity results for the No Leak Paths sample is due to the decreased variability in the manufacture of the coupons due to a lack of carbon fibre tow leak paths. It is expected that with identical surface preparation and curing cycle that similar porosity would be present in the sample due to natural occurrence, and when rounded to one tenth of a per cent this is exactly what occurred. The fact that the No Leak Path samples all showed identical results shows that the manufacture and surface preparation of the samples was consistent and can be removed as a source of variance.

The similar porosities observed between the 40 PSI sample and the No Leak Paths sample confirms the similarity in strength observed in the ASTM D3762 testing. As expected the 40 PSI sample did have more porosity present then the No Leak Paths sample however the difference was of the order of >1% when compared to the 3% difference in porosity between the 70 PSI sample and the No Leak Paths reference. This corresponds to the similar strength results between 40 PSI and the reference whilst the 70 PSI sample showed significantly greater rates of crack propagation.

The variation shown in the 70 PSI and 40 PSI induced porosity samples were expected since it is impossible to guarantee a totally consistent dispersion of the carbon fibre tows when spread from a roughly circular cross-section to a flatter oval cross-section. Of course care was taken to generate reasonably consistent profiles, differences will invariably occur. Since the primary means of air ingress is in the capillaries created between the fibres any variation in cross-section will vary the number of fibres creating enclosed capillaries and as such vary the rate of air ingress. The standard deviation of these two pressure cases is small and shown on the graph below. The expected porosity based on vacuum bag pressure can be predicted with 68.2% confidence to be between the red and green lines. This will be a useful tool for future projects giving expected values of porosity, of course this can be further refined with the addition of tested samples at more varied pressures.

![Expected Porosity vs Vacuum Pressure](image)

Plot 5: Expected Porosity vs Vacuum Bag Pressure

In the initial stages of this project it was planned to undertake structural testing on a series of coupons with porosity varying at 0.5% intervals outwards from 2% as a starting point. For future projects vacuum bag pressure should be started at 55 PSI to target 2% initially. The graph appears to indicate an exponential relationship between pressure and porosity, however this cannot be confirmed with so few data points This would appear to contradict McMullan’s results which found that porosity decreased at higher pressures potentially due to closing of the leak paths by the vacuum pressure forcing the aluminium panels together.

In McMullan’s experiment fewer leak paths were used in proportion to panel size whereas this project used leak paths across an entire edge of a smaller panel to induce porosity. A similar phenomenon of a decline in expected porosity after a peak in increase may be observed at higher pressures than McMullan due to the smaller panel size and relatively larger leak paths to panel ratio, however this point was not reached during testing.

D. Radius of Curvature

Following the ASTM D3762 testing when the samples were forced open it was observed that the aluminium coupons had plastically deformed into an arc. The radius of curvature appeared to be related to the strength of the bond since the lower porosity samples displayed a visibly smaller radius of curvature. The plastic deformation in the coupons occurred as a result of the wedge applying an outward force as it was driven into the bond line. This force caused yielding in the aluminium prior to adhesive failure resulting in the curvature of the coupon.

This provided an opportunity for means of assessing the bending moment and as such the prying force required to fail the adhesive. Given the known geometric and materials properties of the coupons a calculation can be performed to determine the bending moment corresponding to this radius of curvature. The outwards prying force can then be determined from the bending moment using the distance from crack tip to wedge contact with aluminium panels as the lever arm. A diagram of this concept is shown in Figure 5.

The radius of curvature of each specimen can be easily calculated when the specimen is considered as an arc segment of a circle using the formula:

$$\rho = \frac{h}{2} + \frac{w^2}{8h}$$

Where $w$ is the length of a chord drawn on the arc and $h$ is the perpendicular distance from mid span of the chord to the arc.

Since the section has deformed in the partially plastic range, it is impossible to back-calculate a discrete bending moment which would cause the measured radius of curvature. This is because the amount of plastic deformation in the cross-section expressed by the variable $\alpha$ (shown in Figure 6) is unknown. This precludes efficient manual calculations, so to determine the bending moment associated with the radius of curvature finite element modelling (FEM) was employed.

A model was created in the FEM software Abaqus using generic properties for aluminium taken from Callister xxvi shown in Table 7.

![Diagram of figures](Figure 5: Diagram of figures)

**Figure 6: Variable ALPHA (Khennane 2011)**

<table>
<thead>
<tr>
<th>Table 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Property</td>
</tr>
<tr>
<td>Young’s Modulus (E)</td>
</tr>
<tr>
<td>Yield Stress ($\sigma_Y$)</td>
</tr>
<tr>
<td>Poison’s Ratio (v)</td>
</tr>
</tbody>
</table>

The model consisted of a section of the same cross-sectional dimensions as the coupons (25mm x 3mm) and extruded to a depth of 25mm. This depth was chosen to model the static case based on the distance $d$ measured from a coupon as shown in Figure 5. As the wedge shown in Figure 5 is forced through the bond line the crack tip remains at distance $d$ beyond the point of contact between the wedge and coupons, this provides a reasonably constant moment arm for the consistent downwards force applied which is directed outwards as a prying force. By using an encastred boundary condition on the base of the model the instantaneous bending moment conditions can be replicated. A line load was applied to the top edge to replicate the outwards force applied by the wedge. An illustration of the Abaqus model is shown in Figure 7.

By using the formula shown above for $\rho$ the radius of curvature can be calculated from the deformed co-ordinates of a node at the free end and a node at mid span. The force applied can then be calculated from the Abaqus time-step whereby the full load is applied at time = 1 and is applied on a linear ramp from the origin of zero load at time = 0. By matching the average observed deformed radius to the point at which this radius is shown in the FEM the force to achieve this deflection can be determined. The required forces are shown in Table 8.

<table>
<thead>
<tr>
<th>Coupon Series</th>
<th>Average $\rho$</th>
<th>Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Leak Paths</td>
<td>426 mm</td>
<td>1470.9 N</td>
</tr>
<tr>
<td>40 PSI</td>
<td>316 mm</td>
<td>1471.3 N</td>
</tr>
<tr>
<td>70 PSI</td>
<td>264 mm</td>
<td>1471.7 N</td>
</tr>
</tbody>
</table>

These forces all appear remarkably similar for the significant variation seen in the average radius of curvature. However when considering that the coupon has deformed plastically the results are plausible when the assumption that the section is beyond the point of yield yet not at the point off strain hardening. At this section of the stress-strain curve significant deformation can be achieved with minimal variations in applied stress which would lead to increased curvature. In addition the bending moments actually applied to the section will vary with distance $d$. The 25mm used in the model was taken from one of the remaining samples which was originally manufactured for RAAF NDE and is not necessarily representative of coupons of all porosities. It is a valid assumption that coupons with increased porosity would have a larger $d$ since a weaker adhesive would require a smaller outwards force to initiate and propagate the crack, thus with a larger $d$ a smaller prying force would be required to generate the same moment.

In addition to this the model is limited in the materials properties used. Since these were generic values for aluminium rather than specific values the results of the FEM can be taken as a guide only. It is also worth noting that these materials properties have been generated by tensile testing whilst the model is actually replicating a bending situation where half of the section is in compression. More accurate results could be achieved with tensile data taken from testing of one of the coupons; however since the investigation of the adhesive strength-curvature relationship was only initiated late in the project such testing was precluded by time. Whilst the FEM has provided a guide a far more accurate method would be to measure the outwards prying force applied to split the samples and observing the distance $d$ for each coupon to determine the moment. This was not done during this project since the potential to use radius of curvature to observe bending moment was only considered after the samples had been split.

**E. Suitability of ASTM D3762**

It was found during the conduct of this project that the ASTM D3762 Boeing Wedge Test is not the most suitable test in its current form. This is because, as seen above, only two data points were recorded in most cases which provided limited insight into the performance of the adhesive under induced porosity conditions. The test was carried out correctly and performed similar to previous results however the short time of observable crack propagation was a problem.
Whilst none of the samples failed outright under the ASTM D3762 testing varying crack propagation was observed which attests to the relationship between porosity and bond strength. More detail could be determined from these tests if more data points were recorded, since with only 2 points beyond the origin it is impossible to surmise the exact nature of the relationship or attempt to fit a curve to it and determine a formula. This occurred because the prying force and stresses induced by the wedge had dissipated as the crack propagated to the point where equilibrium was reached between these forces and the bond strength within two hours in most cases.

This could simply be overcome by shortening the time interval between measurements however two points must be considered prior to adopting this approach. Firstly, a shorter time interval would require more opening and closing of the environmental chamber necessitated by taking measurements. Since the chamber is relatively small and a low heat source is provided, the elevated temperature and humidity would rapidly dissipate to the point where the sample was at ambient temperature. Conducting the test at ambient temperature would take excessive time so as to be inefficient. Secondly, the accuracy of the measuring implements must also be considered. Since the measurements are taken manually, the accuracy is limited to the ability of the user to observe and mark the results with a stylus. From experience this can achieve an accuracy of one tenth of a millimetre; however this may not be sufficient to discern crack propagations at time intervals shorter than one hour.

A more suitable version of the ASTM D3762 test would have a longer observable crack propagation to generate a greater range of data points. This could be achieved by maximising the prying stresses by increasing the force imparted by the wedge, or decreasing the width of the bond line to decrease bond area. Of the two, a thicker wedge to increase prying forces would be the most suitable since thinner coupons would be more difficult to prepare.

Of even greater advantage in generating a large number of data points would be to abandon the ASTM D3762 test and adopt ASTM D1002 Single Lap Shear testing. Conducting this testing with digital data logging equipment will provide greater accuracy and a greater number of results. This will also rectify the major deficiency in the ASTM D3762 testing as it was conducted in that the failure stresses and bending moments were not able to be recorded since failure of the coupons was forced manually. By failing the coupons in a computerised testing apparatus these measurements could be taken accurately for analysis.

**F. Non-Destructive Evaluation**

During the course of the project the possibility of NDE was investigated with regard to its application in determining the porosity of a bond line. Much of this has been discussed in the project background so will not be revisited. It was found that experimental NDE of coupons using ultrasonics was not a feasible option at ADFA given the dated equipment available. The probes held in the ultrasonics laboratory were too large to provide sufficient resolution so as to detect areas of porosity in the coupons. It was decided from a project management perspective that any practical testing with this equipment would not yield worthwhile results and was abandoned.

There was potential to have NDE technicians from the RAAF conduct reference testing using x-ray and ultrasonics through a former NDE technician studying at ADFA.xxvii Increased x-ray exposure times would result in the higher resolution required to detect areas of porosity. When comparing these results to an ideal reference sample and the Matlab porosity analysis the NDE results could be calibrated to determine porosity. RAAF testing did not occur due to the operational workload of the RAAF NDE technicians, although reference coupons were manufactured. Using the RAAF technicians to conduct NDE proof of concept testing would be worthwhile in the future since the advantages of operational equipment and experienced operators.

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xxvii PLTOFF C. Kluft
VI. Recommendations

It is recommended for future work that the following aspects of the project be maintained:

1. McMullan’s method for inducing porosity using carbon fibre tow leak paths should be maintained with Cytec FM300 film adhesive. This will ensure continuity with the work of previous years and it is a simple and realistic means of inducing porosity. It is reasonably predictable using the curve shown in Plot 5. With a greater range of coupons produced the accuracy of the prediction curve can be improved.

2. That the production of a wide range of porosity induced coupons continues to be a primary aim of the project. This is the only effective method of discerning the exact relationship between porosity and strength.

It is recommended that the following variations be made in future projects:

1. That the variations to ASTM D3762 wedge test be trialled to see if more usable data points can be observed. This will allow the relationship between porosity and crack propagation to be investigated in greater detail. It is also recommended that the coupons be split using a method where the prying force can be directly measured in order to calculate the proportion $\alpha$ which has plastically yielded.

2. That the RAAF be engaged early in the project to conduct NDE of a series of coupons to determine the feasibility of NDE of bond line porosity in the 1.5% to 5% region. This will negate the fact that NDE equipment possessed by ADFA cannot provide sufficient resolution.

3. That a greater emphasis be placed on ASTM D1002 single lap shear testing with computerised measuring equipment. This will provide a higher frequency of recordings with a greater accuracy thus facilitating in-depth analysis of the relationship between porosity and shear strength.

VII. Conclusions

The project has achieved its stated aims in investigating the relationship between bond strength and porosity through the ASTM D3762 Boeing Wedge Test and the potential for NDE to detect porosity was investigated however not conducted. It was found that crack propagation rates were most affected by porosity in excess 1.5% with 0.5% porosity considered the average naturally occurring minimum for the surface preparation and adhesive used. The relationship between bond strength and radius of curvature of the deformed split coupons was investigated with FEM however the results can only be considered as a guide since generic structural properties of Aluminium were used as opposed to specific data. It was considered that the most promising options for NDE were ultrasonics and x-ray since they could feasibly provide sufficient resolution to conduct areas of increased porosity when compared to an existing reference sample.

VIII. Acknowledgements

I would like to acknowledge the contributions of several people to the completion of this project, firstly my supervisor Rikard Heslehurst. His enthusiasm and guidance were invaluable in seeing this project to completion. To my fellow Fourth Year Civil Engineering students; your constant prodding kept me working when I most wanted to stop, and finally to my partner Jessica whose love, support and maintenance of the household when I was consumed with this project has meant the world.
IX. References