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Strength wearout of adhesively bonded joints under constant amplitude fatigue.

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Abstract

The behaviour of adhesively bonded lap joints subjected to fatigue loading is still not well understood. In this paper strength degradation of joints during fatigue cycling is measured experimentally and related to damage evolution. Strength wearout (SW) measurements carried out under constant amplitude fatigue loading of single lap joints are presented and correlated with in-situ measurements of back-face strain (BFS) and estimations of damage progression from fracture surfaces and sectioning of partially fatigued samples. Residual strength was found to decrease non-linearly with respect to the number of fatigue cycles and this corresponded to non-linear increases in the BFS and damage measurements. In particular it was noted that fatigue damage accelerated very quickly towards the end of the fatigue life of a joint. A non-linear SW model is proposed and was found to agree well with the experimental results. This model can be used to predict the residual strength of a joint after a period of fatigue loading once a single empirical constant has been determined.

Keywords: Damage; Fatigue; Fracture; Adhesives; Lap shear; Strength wearout.

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1 Introduction

Bonded joints are replacing conventional joining techniques such as bolted or riveted joints for a number of reasons, including; low weight, high stiffness, ability to join dissimilar materials and more uniform stress distribution. Bonded joints in structural applications will generally experience a wide spectrum of loads in service and in many cases, e.g. in aeronautical, automotive or marine structures, fatigue loading will be a major component of the load spectrum. Hence, understanding the response of the joint to fatigue loads and being able to predict the fatigue life of bonded joints is of great importance. Equally important, especially given the difficulties in predicting fatigue behaviour and the importance it plays in structural failures, is the ability to monitor adhesive joints in-service so that fatigue damage can be detected before failure occurs.

A number of methods of modelling the fatigue behaviour of bonded joints have been proposed, as reviewed in [1, 2]. The most common approach to characterising fatigue behaviour is probably the total life approach in which the number of cycles to failure is plotted as a function of an easily measurable parameter such as the average stress amplitude (the S-N curve) or the maximum fatigue load. One drawback to this method is that no indication is given of the progression of damage in the joints and hence it is of no use in in-service monitoring. An increasingly popular method of in-situ monitoring of damage in bonded joints is the back-face strain (BFS) method, in which changes in the strain signal from carefully positioned strain gauges are used to detect and monitor

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3 damage and cracking in the joint [3-5]. In a recent paper, the authors combined the BFS
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5 technique with finite element analysis (FEA) and optical examination of damage to
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7 extend the total life method to include different regions of crack growth [6]. It was shown
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9 that damage and crack development in the joints varied depending on the fatigue load and
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11 a model was proposed that, together with BFS measurements could be used to monitor
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13 in-service integrity. However, a remaining drawback of the technique is that it relies on
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15 extensive experimental data that is specific to a particular joint type. Progressive damage
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17 modelling approaches attempt to overcome this limitation by relating a generally
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19 applicable failure parameter to the rate of cracking or damage evolution. The most
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21 popular variant of this method for bonded joints is to relate strain energy release rate (G)
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23 to the fatigue crack propagation rate (da/dN) through an empirical crack growth law in
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25 which the crack growth law parameters are determined experimentally [7-12]. This
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27 approach is potentially very powerful and has met with some success, however,
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29 difficulties remain, such as accounting for crack initiation [13], environmental effects
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31 [14,15], complex failure paths [14-16], creep effects [17-18] and load history effects [19-
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33 20] and requires further development before it can be used with confidence for a wide
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35 range of joints.
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45 A third approach to predicting fatigue failure is to use phenomenological models, in
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47 which the number of fatigue cycles is related to the residual strength or stiffness. The
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49 advantage of the residual stiffness approach is that stiffness can be measured non-
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51 destructively and in-situ [21-23], however, applying a failure criterion to the residual
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53 stiffness models is not straightforward [24-25]. Additional problems with adhesive joints
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is that global stiffness measurements may not be very sensitive to damage in the adhesive and it is difficult to differentiate between cracking, damage and creep from stiffness measurements of viscoelastic materials, such as adhesives [26].

In the residual strength approach, strength degradation during fatigue is characterized by relating the residual strength from quasi-static testing a partially fatigued sample, $S_R(n)$ to the number of fatigue cycles, n . This is initially equal to the static strength, S_u , but decreases as damage accumulates during the fatigue cycling. Failure occurs when the residual strength equals the maximum stress of the spectrum, S_{max} , i.e. when $S_R(N_f) = S_{max}$. The rate of strength degradation mainly depends on S_u , S_{max} and R (S_{min} / S_{max}), i.e.:

$$S_R(n) = S_u - f(S_u, S_{max}, R)n^\kappa \quad (1)$$

where κ is a strength degradation parameter. Substitution of the failure criterion ($S_R(N_f) = S_{max}$) into Eq. (1) gives:

$$f(S_u, S_{max}, R) = \frac{S_u - S_{max}}{N_f^\kappa} \quad (2)$$

and the residual strength, $S_R(n)$, can be defined as:

$$S_R(n) = S_u - (S_u - S_{max}) \left(\frac{n}{N_f} \right)^\kappa \quad (3)$$

This approach has been extensively applied to fibre reinforced polymer composites [27-31] and has been extended to include variable amplitude fatigue [32,33]. There has been

little application of this approach to adhesively bonded joints, however, Erpolat et al [34], used a modified strength wearout approach to model failure of CFRP double lap joints under variable amplitude fatigue. A linear strength wearout was assumed and a cycle mix factor was introduced to account for damage interaction effects. This approach was seen to result in considerably better predictions of fatigue life in bonded joints under variable amplitude fatigue than the traditional Palmgren-Miner approach.

The advantage of the residual strength method is that there is an intrinsic failure criterion, however, the disadvantage is that destructive testing is required to characterize the strength degradation. Hence a relationship between the residual strength and a non-destructive, easily measurable parameter would be extremely useful. This paper presents an experimental investigation of the strength degradation in adhesively bonded single lap joints subjected to constant amplitude fatigue. The residual strength is then related to damage and cracking in the joints, as measured from the fracture surfaces and from the polished cross sections of partially fatigued joints. Finally, both residual strength and damage are related to back-face strain (BFS) measurements, which can be continuously monitored during fatigue testing.

2.0 Experimental

2.1 Sample manufacture

The adhesively bonded single lap joints (SLJ's) used in this work were manufactured to British standard [35]. Fig. 1 (a) shows the dimensions of the SLJ. The location of strain gauges used to measure the backface strain is shown in Fig. 1(b). The geometry of the adhesive fillets can also be seen in this figure. The radius, R of the fillet ranged from 0.3

to 0.5mm and the length 'd' ranged from 0.4 to 0.6 mm. Clad aluminium alloy 7075-T6 was used for the adherends and the adhesive used was FM 73M (Cytec Engineered Materials). This is a single part toughened epoxy adhesive with a nominal thickness of 0.2mm which is supported by a random carrier mat. The material properties for adhesive and substrate are given in Table.1. Material properties for the adhesive are taken from the tensile testing of bulk adhesive specimens under ambient conditions and for the aluminium alloy they are taken from the manufacturer's data sheet. Two different thicknesses of adherend were used in the experimental programme. Initially, 2.5mm thick adherends were used, however, failure in the aluminium at high cycles, prompted a change to 3mm thick substrates in later experiments.

Fig. 1 (a) SLJ dimensions, (b) strain gauge locations and the fillet geometry.

Table 1 Material properties

	Aluminium (7075-T6)	Adhesive (FM73M)
E (GPa)	70.0	2.00
ν	0.33	0.38

The aluminium adherends were ultrasonically cleaned in an acetone bath for five minutes prior to an AC DC anodisation surface pre-treatment [36]. This treatment is proposed as an environmentally friendly alternative to current chromate containing processes. The substrate to be treated is one of the electrodes in an electrochemical cell with a titanium electrode and an electrolyte containing a weak mixture of phosphoric and sulphuric acid (5%). An alternating current (AC) is ramped up to 15 V over a period of 1 minute and maintained for a further 2 minutes. The current is then changed to direct current (DC) and increased to 20 V. The bath is kept at this voltage for a further 10 minutes. After the pre-treatment, the specimens were washed with distilled water and dried. In order to study the pre-treated surface, anodised samples were fractured by bending in a bench vice.

(a)

(b)

(c)

Fig. 2. (a) AC DC oxide layer (layers B and C) on clad aluminium (layer A) (b) structure of the DC oxide layer (layer B) and (c) porous structure of the AC oxide layer (layer C).

Micrographs of the fracture surface taken using field emission gun scanning electron microscopy (FEGSEM) are shown in Fig. 2. Three layers can be seen in Fig. 2(a). Layer A is the aluminium cladding, layer B is the oxide layer formed during DC anodisation and layer C is the oxide layer formed during AC anodisation. It can be seen that layer B is thinner but denser than layer C. A magnified image of layer B is shown in Fig. 2(b). This layer forms a barrier capable of offering enhanced corrosion resistance to the surface

of the aluminium alloy [37]. Layer C, as shown in Fig. 2(c), is more porous, and provides an excellent surface for adhesive bonding.

Directly after the AC DC surface treatment, a thin film of BR 127 corrosion resistant primer was applied to the surface to be bonded. The thickness of the primer layer on application ranged from 15 to 25 microns. The primer was left to dry at room temperature and then cured at 120°C for half an hour. The adherends were returned to room temperature and kept in a desiccator prior to bonding. The adhesive was taken from the freezer and brought to room temperature in a desiccator or sealed bag before bonding in order to minimise moisture in the adhesive layer. The adhesive was cured at 120°C for 1 hour with a constant applied pressure. The bonded joints were then stored in a dessicator at room temperature prior to testing.

2.2 Mechanical testing

The joints were tested quasi-statically using an Instron 6024 servo-hydraulic testing machine with a constant displacement rate of 0.1mm/sec. The same machine was used for fatigue testing the joints in load control with a load ratio of 0.1 and a frequency of 5 Hz. Sample were tested with constant load amplitude, sinusoidal waveforms. Various maximum loads were used and these were determined as a percentage of the mean quasi-static failure load (QSFL). Tests were carried out at ambient temperature and relative humidity, which ranged from 22-25°C and 40-50%, respectively, during the tests. Back-face strain (BFS) was used to monitor damage in selected joints during the fatigue testing. A more detailed description of the location of the strain gauges and the measurement procedures is given in previous work by the same authors [6]. Table 2

shows the test parameters for both quasi-static and fatigue loading, together with the number of specimens tested.

Table 2 Test parameters.

Type of loading	Total number of specimens	Load ratio	Frequency [Hz]	Adherend thickness [mm]	Adherend width [mm]
Quasi-static	4	-	-	2.5 and 3	25
Fatigue	27	0.1	5	2.5 and 3	25

In order to determine the strength wearout characteristics of the joints, the residual failure loads of partially fatigued joints were determined. A set of joints with similar sized fillets was selected for fatigue testing with a particular maximum load. Two or more samples were tested to failure and then others were fatigued for a selected percentage of the number of cycles required for failure. A number of these were sectioned to assess damage, as described in the next section, and the remainder were tested quasi-statically to determine the residual strength, which was expressed in terms of the QSFL.

2.3 Optical microscopy and SEM

A number of partially fatigued joints in each set were sectioned in order to assess damage. The joints were sectioned using a band saw at three locations; L-L₁, C-C₁ and R-R₁, as shown in Fig. 3. The sections L-L₁ and R-R₁ were 6-8mm from the edge of the sample and section C-C₁ was in the centre of the sample width. The sectioned samples were mounted and progressively polished to a 1µm finish to remove any visible damage

caused by the sectioning process. The polished sections were examined optically and using field emission gun scanning electron microscopy (FEGSEM). The FEGSEM was carried out using a LEO 1530VP instrument operating with primary beam energies of either $8 \times 10^3\text{V}$ or $20 \times 10^3\text{V}$. The samples used for FEGSEM were gold coated to prevent charging.

Fig. 3. Section locations on the joint.

Fracture surfaces from both the fully fatigued and strength wearout samples were examined, using both optical microscopy and FEGSEM. In the strength wearout samples a differentiation could be made between the crack growth during fatigue and that in the quasi-static testing to determine residual strength. This provided an additional method of quantifying the evolution of damage in the joints during fatigue testing.

3.0 Results

3.1 Mechanical test results

The mean QSFL for the SLJ's with 2.5mm thick adherends was 11.95kN with a standard deviation of 0.25. The SLJ's with 3mm thick adherends had a mean QSFL and standard deviation of 12.5kN and 0.31 respectively. The maximum fatigue load is plotted against

the number of cycles to failure for those samples fatigue tested to failure in Fig. 4 (a). Sets of results for joints with substrate thicknesses of 2.5 and 3mm can be seen, however, the difference between the fatigue life of the two sets of joints is negligible within the scatter of the results. At maximum fatigue loads lower than 6.5kN, failure was in the adherend for those joints manufactured with 2.5mm thick aluminium, as shown in Fig. 4(b). However, for the joints manufactured with 3mm thick aluminium, failure was in the adhesive layer for all loads. This can be attributed to the reduction in stress in the aluminium for a given load having a significant effect on its fatigue life.

Fig. 4. (a) L-N curve with 2.5 and 3mm adherend thickness, (b) adherend failure in joint with 2.5mm adherend thickness.

In all cases in which failure was in the adhesive, rather than the adherend, the failure appeared to be cohesive failure of the adhesive from optical microscopy. This was

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3 examined further by bending selected fractured surfaces in a bench vice to view in the
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5 FEGSEM. Typical micrographs can be seen in Fig. 5. Fig 5(a) is a relatively low
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7 magnification micrograph in which fractured islands of oxide can be seen on the
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9 plastically deformed aluminium surface. A magnified view of the edge of one of these
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11 islands can be seen in Fig 5(b), which shows the aluminium alloy, oxide and adhesive
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13 layers. It can be seen that failure is in the adhesive layer, however, this can be close to
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15 the oxide interface. Fig. 6 shows the FEGSEM micrograph of a polished section of a
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17 fracture surface from a fatigue tested sample. Micro cracks can be seen in the adhesive
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19 layer as well as the cavities associated with rubber toughening that have been explained
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21 previously by a number of authors [38-41]. The transverse micro-cracks are indicative of
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23 additional damage in the process zone.
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(a)

(b)

Fig. 5. (a) Cohesive failure shown on bent fracture surface, (b) magnified image of fracture surface.

Fig. 6. Polished cross section of fracture surface showing interface between adhesive and aluminium oxide layer.

3.2 Strength wearout test results

In this section, the results from the SW experiments are described. Strength here is characterised by the QSFL of the joint after it had been fatigued for a certain number of cycles. Fig. 7 shows the results from these experiments for 3 different maximum load values in the fatigue testing. A non-linear reduction in the residual strength as a function of fatigue life can be seen for all the curves. The rate of strength wearout increases rapidly towards the end of the fatigue life. This is sometimes referred to as ‘sudden death’ type failure. Once the residual strength has decreased such that the QSFL has reached the value of maximum load in the fatigue cycle then quasi-static failure occurs. This is indicated by the vertical line at the end of each strength wearout curve.

Fig. 7. Residual failure load curves for different fatigue loads taken as % of QSFL.

Eqn. 4, which is Eqn. 3 in terms of load rather than stress, has been fitted to the SW data, as indicated by the lines in Fig. 7.

$$L_R(n) = L_u - (L_u - L_{\max}) \left(\frac{n}{N_f} \right)^\eta \quad (4)$$

where, $L_R(n)$ is the residual load calculated as the function of fatigue cycles n , L_u is the QSFL, $L_{\max}$ is the maximum fatigue load, N_f is the number cycles to failure, which is a constant for a given fatigue load. η is an empirical parameter that indicates the nature of strength degradation, with $\eta = 1$ representing linear degradation $\eta > 1$ representing accelerating or “sudden death” behaviour and $\eta < 1$ representing rapid initial loss. In Fig. 7, η varies between 1.8 and 2.8.

4.0 Damage characterisation

4.1 *In-situ damage characterisation using BFS measurement*

In this section, the results from the back-face strain (BFS) measurements are summarised. Further description of this method can be found in [3-5]. In Fig. 8(a), the maximum BFS is plotted against number of fatigue cycles for fatigue tests with maximum loads of 63% and 54% of the QSFL. The difference in initial strain between SG1 and SG2 is due to unequal sized fillets at the ends of the overlap, as discussed and proven using FEA in the earlier work on BFS by the same authors [6]. Three regions can be seen in both of the curves; an initial crack initiation region (region I), a slow crack growth region (region II) and a fast crack growth region (region III).

(a)

(b)

Fig. 8. (a) BFS plots for higher fatigue loads (SG1), (b) BFS plot for maximum fatigue load of 40% of QSFL.

As expected, the strains are higher and the number of cycles smaller for the sample tested at the higher load. In Fig. 8(b), BFS is plotted against number of fatigue cycles for a fatigue test with a maximum fatigue load of 40% of QSFL. In this case most of the fatigue life time appears to be spent in crack initiation, with a sudden rapid increase in strain close to failure. The effect of fatigue load on damage evolution is illustrated more clearly in Fig. 9, where the normalised BFS is plotted against normalised number of cycles. In this case crack growth was from both ends of the overlap. In some cases crack growth is predominantly from one side, as discussed in detail in [6].

Fig. 9 (a) Normalised BFS plots (SG1), (b) Typical crack path

4.2 Microscopic characterisation

4.2.1 Optical microscopy of sectioned joints

The observed decrease in residual strength and increase in BFS during fatigue testing indicates progressive cracking or other forms of damage in the joints during fatigue. The nature of this damage was investigated by examination of the polished sections of partially fatigued samples. It was seen that damage initiated in the fillet area of the adhesive at the end of the overlap, adjacent to the embedded corner of the adherend. This damage developed into a crack with further fatigue testing and then propagated along the bond line and through the fillet. Damage and crack lengths were greater for section C-C₁ than for the edge sections. A summary of the measured damage and crack lengths from the C-C₁ sections can be seen in Fig. 10. Cracks were not seen until damage lengths of approximately 2mm, after this the figure shows crack length only. For the joint with a maximum fatigue load of 63% of the QSFL, the first sign of damage was seen in the adhesive at approximately 1500 cycles and cracking was seen after approximately 3000 fatigue cycles. The damage and cracking initiated in the fillet area of the adhesive close to the embedded corner of the adherend. Crack growth was then both towards the fillet surface and along the bondline and was observed at both ends of the overlap. The damage and crack lengths in Fig. 10 are a summation of damage or cracking at both ends of the overlap in the middle of the joint width, this being, where damage was greatest. It can be seen that the crack length increases rapidly towards the end of the fatigue life. Similar trends were seen for the other fatigue loads and it can also be seen by comparing Figs. 8 and 10 that there is some similarity between the evolution of the BFS and damage during fatigue testing.

(a)

(b)

Fig. 10. Damage and crack length vs. number of fatigue cycles for max. fatigue load of (a) 63% and 54% of QSFL, (b) 40% of QSFL. All measured at the middle of the joint width.

4.3 Optical microscopy and FEGSEM of fracture surfaces

Fig. 11 shows the fracture surfaces for joints tested with a maximum fatigue load equal to 63% of the QSFL. Two regions can be seen here, which are labelled FCG (fatigue crack growth) and QSCG (quasi-static crack growth). It can be seen that the extent of the FCG region increases with the number of fatigue cycles. A similar trend was seen for other fatigue loads and a summary of the measured FCG lengths at the centre of the sample widths can be seen in Fig. 12. A similar non-linearity of damage is observed to that seen in the polished sections of partially fatigued samples, as shown in Fig. 13.

Fig. 11. Fracture surfaces for maximum fatigue load of 63% of QSFL after (a) 1500 cycles, (b) 3000 cycles and (c) 4000 cycles.

It is interesting to note that although the same trend is seen with the two techniques, that the FCG length measured from the fracture surfaces is greater than the crack lengths measured from the sections in each case. This could be because of a number of reasons

including, sample to sample variation, the fact that the sections may not have been made at the point of greatest crack length, the crack length may have been underestimated from the polished sections and that the FCG length may include some initial crack growth in the quasi-static testing. It is interesting to note that the difference between the two methods of assessing damage increases as the fatigue load decreases. This is a possible indication of the role of sub-critical damage evolution in the extended initiation periods for samples tested close to the fatigue threshold.

Fig. 12. Fatigue crack growth (FCG) lengths measured from fracture surfaces.

(a)

(b)

(c)

Fig. 13. Comparison of damage measured from sections and FCG measured from fracture surfaces for max. fatigue loads of (a) 63% of QSFL, (b) 54% of QSFL and (c) 40% of QSFL.

Three different regions could be seen in the fracture surfaces, the FCG and QSCG regions described in the previous section and the fillet regions, in which crack initiation occurs. These regions were examined in more detail using FEGSEM and typical results are shown in Fig. 14. Fig. 14(a) shows the fillet region in which there is relatively little cavitation and cavity size is small. In this region crack growth is slow, predominantly mode I and follows a gradual evolution of micro-damage prior to crack formation. The small cavities could be because there is little cavitation of the rubber toughening particles. A greater size and extent of cavities are seen in the FCG regions, as shown in Fig. 14(b). In this region, crack growth is stable and is a mix of Modes I and II. The

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3 increased cavitation is indicative of more active toughening by the rubber phase. In the
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5 QSCG region the crack growth is much greater and results in a rougher fracture surface,
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Fig. 14. SEM of fracture surfaces at (a) fillet region, (b) fatigue crack growth region (FCG), (c) quasi-static crack growth region (QSCG).

5.0 Discussion

5.1 Residual strength, damage and BFS

It has been found that the residual strength of the bonded lap joints tested decreased non-linearly with the number of fatigue cycles and that there was a corresponding increase in the indications of damage. The results are summarised in Figs. 15-17 which show, normalised values of (a) change in BFS (referred to as dBFS), (b) FCG length and (c) crack or damage length from the sectioned joints (sec. damage) as a function of the normalised residual failure load in quasi-static testing. These results for sectioned damage, crack, FCG and dBFS are obtained through linear interpolation of the damage, crack and BFS curves shown in Figs. 8, 12 and 13. Corresponding points for the residual loads are obtained from Fig. 7. In Fig. 15 the results for joints fatigue tested with a

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3 maximum fatigue load of 63% of the QSFL are shown. A relatively linear increase in
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5 BFS and crack length can be seen as the residual strength decreases. Fig. 16 shows the
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7 results for the samples fatigue tested with a maximum fatigue load of 54% of the QSFL.
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9 Again, it can be seen that the BFS and measures of damage/cracking show similar trends,
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11 although in this case the crack growth appears to be in three distinct stages; an initial
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13 decreasing trend, a linear (approximately) region and an accelerating region towards final
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15 failure. In Fig. 17 the results for the sample fatigue tested with a maximum fatigue load
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17 of 40 % of the QSFL can be seen. In this case both FCG length and the damage length
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19 measured from the polished sections increase progressively with decrease in residual
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21 strength whereas the BFS doesn't show any change until towards the end of the fatigue
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23 life. This may indicate that the decrease in the strength of the joint is due to both
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25 damage and crack growth and that BFS is less effective at detecting micro-damage than
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27 cracking. It should also be noted that in fatigue testing of bonded joints a significant
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29 degree of sample to sample variation is seen which should be taken into account when
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31 analysing results. A summary of the fatigue results including standard deviations can be
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33 seen in Table 3. It can be seen from this figure that there is a high degree of scatter in the
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35 fatigue testing.
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Fig. 15. Normalised dBFS, FCG and sectioned damage/crack lengths as a function of the normalised residual load for max. fatigue load of 63% of QSFL.

Fig. 16. Normalised dBFS, FCG and sectioned damage/crack lengths as a function of the normalised residual load for max. fatigue load of 54% of QSFL.

Fig. 17. Normalised dBFS, FCG and sectioned damage/crack lengths as a function of the normalised residual load for max. fatigue load of 40% of QSFL.

Table 3. Summary of results from fatigue tests

Max. fatigue load (% of QSFL)	Average cycles to failure	Standard deviation
63	13366	6373
54	71104	56281
40	204492	147795

5.2 Non-linear strength wearout model (NLSWM)

Bearing in mind the results discussed in the previous sections, a non-linear strength wearout model (NLSWM) is proposed for strength degradation in bonded joints subjected to fatigue loading. The model below is a modified version of that used by Schaff and Davidson [32,33], as given in Eqn (3). The following normalised parameters can be introduced:

$$N_n = n/N_f \quad (5)$$

$$L_n = L_R(n)/L_u \quad (6)$$

Substituting (5) and (6) into Eqn. (4):

$$L_n = 1 - \frac{(L_u - L_{\max})}{L_u} (N_n)^\eta \quad (7)$$

Fig.18. Nonlinear strength wearout model

Fig. 18 shows experimental plots of L_n against N_n , together with the best fit of Eqn. (7). It can be seen that the proposed phenomenological model agrees well with the experimental results. A single SW curve can be reasonably drawn for the entire range of fatigue loads wherein, the experimental parameter η is independent of the applied fatigue load and is hence a powerful predictive tool. In Fig. 18 the line of best fit was with a value of η of 1.65. For the experimental data in Fig. 18, the standard deviation (σ) was 0.17, and this is indicated by the dashed lines in the figure. The data can be fitted to a normalised probability distribution with mean equal to L_n and σ equal to 0.17. The governing equation for this distribution is given in Eqn. (8).

$$L_{ni} = \left[\frac{I}{\sigma 2\pi} e^{-\frac{I}{2} \left(\frac{N_n - L_n}{\sigma} \right)^2} \right] \quad (8)$$

where, L_{ni} is the probabilistic value of normalised residual load for a value of N_n . This can be used to determine the probability of failure at a given load after a given fatigue life.

Conclusions

Residual strength measurements of single lap joints subjected to constant amplitude fatigue have been made and correlated with in-situ measurements of back-face strain (BFS) and estimations of damage and cracking in the joints from the fracture surfaces and from the polished sections of partially fatigued samples. Residual strength was found to decrease non-linearly with respect to the number of fatigue cycles and this corresponded

to non-linear increases in the BFS and damage measurements, with fatigue damage acceleration towards the end of the fatigue life of a joint. It was also seen that the value of the maximum fatigue load affected damage evolution in the joints, with longer crack initiation periods seen at lower fatigue loads. A non-linear strength wearout (SW) model was proposed to characterise the strength degradation during fatigue and this was found to agree well with the experimental results. This model can be used to predict the residual strength of a joint after a period of fatigue loading once a single empirical constant has been determined by conducting strength wearout tests on the particular joint in question.

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Response to Referees Comments

All the referees comments are reproduced below in italics, followed by a detailed description of how they have been addressed

Reviewer #1: Comments to the authors:

Page 6: Please add more information about the fillet (size, geometry, variation of both).

Fig 1(b) has been added to show the fillets and the following has been added to Section 2.1, paragraph 1:

“The geometry of the adhesive fillets can also be seen in this figure. The radius, R of the fillets ranged from 0.3 to 0.5mm and the length ‘ d ’ ranged from 0.4 to 0.6 mm.”

Page 7/8: According to the description, the AC current was applied first and subsequently the DC current. Fig. 2(a), however, shows a sequence Alu-DC-AC. How can this be explained? What is the layer above Layer C - is this the primer or already the adhesive? How thick is the layer of the primer?

Oxide coatings grow from the metal surface, therefore, the oxide layer adjacent to the metal will correspond to the most recently applied conditions (DC in this case). The referee seems to have a misunderstanding regarding the nature of oxide formation.

Concerning the second point, there is no layer above layer C. As stated in Section 2.1:

“In order to study the pre-treated surface, anodized samples were fractured by bending in a bench vice. Micrographs of the fracture surface taken using field emission gun scanning electron microscopy (FEGSEM) are shown in Fig. 2”

It is clear, therefore, that there can be no primer or adhesive in Fig. 2. I think the “*layer above layer C*” the referee is referring to is in fact the surface of layer C, which can be seen in addition to the cross section because of the angled viewpoint.

As stated above, there is no primer in Fig. 2. The primer layer on application was approximately 15-25 microns and this is now mentioned in Section 2.1. However, this has no relation to the bonded joint as the primer becomes indistinguishable from the adhesive layer on bonding.

Page 9/10, 2.2: Add a table showing the set-up: parameters, number of specimens, etc. Show the BFS location in Fig. 1.

The following table has been added, as requested.

Table 2 Test parameters.

Type of loading	Total number of specimens	Load ratio	Frequency [Hz]	Adherend thickness [mm]	Adherend width [mm]
Quasi-static	4	-	-	2.5 and 3	25
Fatigue	27	0.1	5	2.5 and 3	25

BFS location is now shown in Fig. 1, as requested.

Page 10, 2.3: How were the joints sectioned and what was the potential damage caused by this process (including polishing?)

The following has been added to Section 2.3:

“The joints were sectioned using a band saw at three locations; L-L₁, C-C₁ and R-R₁, as shown in Fig. 3. The sections L-L₁ and R-R₁ were 6-8mm from the edge of the sample and section C-C₁ was in the centre of the sample width. The sectioned samples were mounted and progressively polished to a 1µm finish to remove any visible damage caused by the sectioning process.”

Page 13/14: Is Fig. 5(a) a top view? If yes and taking into account the scale it seems that failure was not clearly cohesive but close to the interface/bondline?

This is valid a valid point and the following has been added to Section 3.1:

“It can be seen that failure is in the adhesive layer, however, this can be close to the oxide interface.”

Fig. 5(b) is not clear. Taking into account the scale, the white layer designated "adhesive" can only be the interface, which seems to contain cracks parallel to the layer? Is the primer layer not visible? This photo also indicates failure in the bondline/interface rather than cohesive failure .?

The first point makes no sense as it is impossible for a ‘layer’ to be an ‘interface’. The top layer in the figure is the adhesive, as labelled. There are no parallel cracks in the figure. As described (both in text and figure caption), this is a fracture surface and what is seen is simply the fracture surface of the adhesive. As stated previously, the primer is indistinguishable from the adhesive on curing. There is a likelihood that material adjacent to the interface will differ from that in the bulk adhesive, however, this is a complex issue that is not the subject of this paper. The inference that the primer remains distinct from the adhesive layer after curing and may be visible in a micrograph is simply incorrect.

Fig. 6. again is not clear. The adhesive layer looks differently compared to Fig. 5(a). Why are the cracks in transverse direction and not along the bondline/interface?

The adhesive layer in Fig. 6 looks different to that in Fig 5 because it is polished surface rather than a fracture surface (as clearly stated in the text and figure captions). The following has been added regarding the transverse microcracks:

“The transverse microcracks are indicative of additional damage in the process zone.”

Page 19: Line 4, a corresponding clear photo showing the crack location in the bondline should be shown. How was the crack length measured?

A comment about the ratio of the crack length from both ends should be given: where they almost equal or did one crack predominate.

Why was the limit of "damage" set at 2 mm crack length (in Fig. 10)?

The questions raised here are fully discussed in a previous paper by the authors, as already indicated in the first sentence of Section 4.1. However, Figure 9(b) has been added showing typical crack location and the following has been added to the description of the figure:

“In this case crack growth was from both ends of the overlap. In some cases crack growth is predominantly from one side, as discussed in detail in [6].”

The following has been added to the description of Fig. 10 to address the last point:

“Cracks were not seen until damage lengths of approximately 2mm, after this the figure shows crack length only.”

Page 24-26: Does an explanation exist for the different morphologies of the crack surfaces (fillet, FCG and QSCG region)?

Description of Fig. 14 has been expanded to :

“Fig. 14(a) shows the fillet region in which there is relatively little cavitation and cavity size is small. In this region crack growth is slow, predominantly mode I and follows a gradual evolution of micro-damage prior to crack formation. The small cavities could be because there is little cavitation of the rubber toughening particles. A greater size and extent of cavities are seen in the FCG regions, as shown in Fig. 14(b). In this region, crack growth is stable and is a mix of Modes I and II. The increased cavitation is indicative of more active toughening by the rubber phase. In the QSCG region the crack growth is much greater and results in a rougher fracture surface, as shown in Fig. 14(c).”

Page 27: last line: A table with testing results (mean values and standard deviations for each parameter combination, etc. see comment to page 9/10) should be given to make it possible to assess the results.

The following table and description have been added:

“A summary of the fatigue results including standard deviations can be seen in Table 3. It can be seen from this figure that there is a high degree of scatter in the fatigue testing.”

Table 3. Summary of results from fatigue tests

Max. fatigue load (% of QSFL)	Average cycles to failure	Standard deviation
63	13366	6373
54	71104	56281
40	204492	147795

Page 29: It is not clear what the modification of the Schaff and Davidson version is. Specify the range of applicability of the model (type of joints and materials).

The modification can be seen by comparison with Eqn (3). This is now made more clear by adding the following to Section 5.2:

“The model below is a modified version of that used by Schaff and Davidson [32,33], as given in Eqn (3).”

The second point is impossible to answer without the relevant data as this is a phenomenological model (as stated).

Page 32: How is this "single empirical constant" determined in a practical application? On page 5, the impression is received that the proposed method provides a "relationship between residual strength and a non-destructive, easily measurable parameter". Please clarify this important point.

This is a phenomenological model. The parameter is determined by conducting strength wearout tests and fitting the equation to the data, as shown in the paper. The following has been added to the conclusions to emphasise this:

“This model can be used to predict the residual strength of a joint after a period of fatigue loading once a single empirical constant has been determined by conducting strength wearout tests on the particular joint in question.”

The “*relationship between residual strength and a non-destructive, easily measurable parameter*” is already mentioned in the Conclusions in the sentence:

“Residual strength measurements of single lap joints subjected to constant amplitude fatigue have been made and correlated with in-situ measurements of back-face strain (BFS) and estimations of damage and cracking in the joints from the fracture surfaces and from the polished sections of partially fatigued samples.”

Reviewer #2: The authors presented substantiate experimental results to prove their claim. However, there are some places where more detailed explanations are needed. The authors have to check or clarify the following points.

1. Fig. 4(a)

Only 2.5 mm thick specimens at maximum fatigue loads lower than 6.5 kN showed the adherend failures, while the other specimens showed adhesive failures. Why? Would you explain the difference of the failure mechanism?

The following has been added to section 3.1

“This can be attributed to the reduction in stress in the aluminium for a given load having a significant effect on its fatigue life.”

2. Fig. 8 (b)

Clarify the "SG 1" and "SG2". If the SG1 and SG2 indicate two strain gages at the same location of two adherends, why are these two strain values different in Fig. 8 (b)? And which strain do you use in Fig 8 (a), and 40% data of Fig. 9 (SG1 or SG2?)

Strain gauge location is now shown in Fig. 1(b).

The following has been added to Section 4.1. to address the second point:

“The difference in initial strain between SG1 and SG2 is due to unequal sized fillets at the ends of the overlap, as discussed and proven using FEA in the earlier work on BFS by the same authors [6].”

On the final point, the strain gauge is now indicated in the figure title.

3. Fig. 18

Is it correct that the abscissa axis of the probability distribution has some tilt angle (seems to be perpendicular to NLSWM curve)? Should this axis be perpendicular to horizontal axis?

To avoid possible confusion, the probability distribution has been changed to an insert in Fig. 18.