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ON SUBSURFACE CRACK GROWTH IN FIBRE METAL LAMINATE MATERIALS

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ABSTRACT

Fatigue crack growth in fibre metal laminates (FMLs) is significantly more complex than in monolithic materials due to the interaction of various physical mechanisms that govern the growth of cracks in laminates. Extensive research has gone into the development of analytical models that try to predict the growth of surface and through-cracks in the FML Glare under fatigue loading. To date, less emphasis has been placed on developing fatigue crack growth models for part through cracks. These part-through cracks exhibit different rates of growth for each layer of the laminate based upon differing stress levels and delamination zone sizes. To better predict the residual strength of FML structures, understanding the behavior of subsurface crack growth is required. For this reason, data of crack growth rates for layers of various laminates were compared to an analytical fatigue crack growth model developed for surface cracks in a specific type of FML, Glare. This paper gives an initial assessment of the model's veracity for subsurface crack growth.

KEY WORDS: Fibre Metal Laminates, Fatigue, GLARE

1. INTRODUCTION

In today's aerospace market, the need for materials that are lighter and stronger is greater than ever. In order to remain competitive, a large passenger or cargo aircraft must maximize its fuel efficiency and cargo capacity, all the while minimizing maintenance costs. In order to help meet these needs, a material system called Glare was developed. Approximately 10% lighter than aluminum for sheets of the same thickness, Glare possesses significantly better fatigue and damage tolerance properties than monolithic aluminum.

Glare is a member of the family of material systems known as Fibre Metal Laminates (FMLs). FMLs are characterized by their construction of alternating layers of metal and uniaxial fibers. Glare in particular consists of thin (between 0.3mm and 0.5mm typically) aluminum sheets and uniaxial glass fibres. The glass fibres are laid up in various configurations of ply orientation to maximize material properties for a given application. For example, the Glare configuration tested in this investigation was Glare 4A-4/3-0.4. This configuration is outlined in Table 1.

Table 1: Glare 4A-3/4-0.4 stack up sequence.

| Layer | Constituent |
|-------|---|
| 1 | 0.4 mm Al2024-T3 L |
| 2 | 0.375 mm 90°/0°/90° Glass Fibre Prepreg |
| 3 | 0.4 mm Al2024-T3 L |
| 4 | 0.375 mm 90°/0°/90° Glass Fibre Prepreg |
| 5 | 0.4 mm Al2024-T3 L |
| 6 | 0.375 mm 90°/0°/90° Glass Fibre Prepreg |
| 7 | 0.4 mm Al2024-T3 L |

The presence of glass fibres in the lay-up gives Glare its superior fatigue properties. When a fatigue crack initiates in Glare, the fibers adjacent to the aluminum ply carry some of the load over from the crack. This is termed fibre bridging, and the concept is shown in Figure 1. This phenomenon is a very complex, yet self-balancing occurrence. As the crack propagates, the fibers around the crack delaminate from the aluminum ply. This delamination always follows very close to the crack tip. The delamination frees a greater length of the fibers to be put in tension due to the crack opening displacement. With the greater length of fiber carrying the load, the stresses in the fibres are reduced. This bridging helps to restrain the crack from opening, thus reducing the effective stress intensity at the crack tip. By reducing the stress intensity, the crack growth rate is reduced. Glare is seen to have nearly constant crack growth rate through much of its fatigue life when the fibre layers are in line with the applied loads.

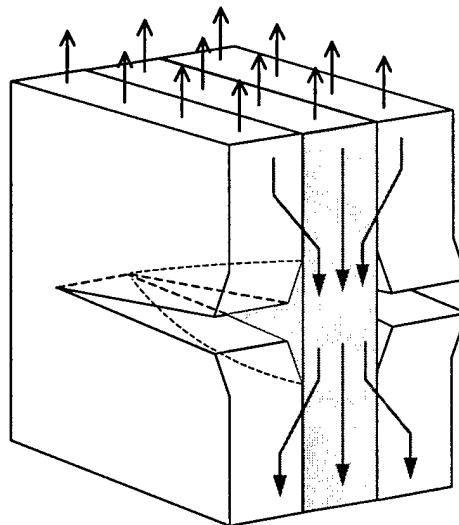


Figure 1: Fibre Bridging in Glare FML [1].

Fatigue crack growth characteristics for surface and through the thickness cracks in Glare are relatively well understood. However, further knowledge is needed about how cracks propagate at the subsurface level to gain a better understanding of Glare's damage tolerance. This will aid engineers in designing riveted joints, where cracks typically initiate at the interface between the two joined sheets of material and a rivet. It is challenging to inspect for these hidden cracks, requiring the use of sophisticated NDI equipment such as eddy-current probes. If the crack

growth behavior of subsurface cracks can be well understood, it may be possible to increase the intervals between inspections of these riveted joints.

2. BACKGROUND

To describe surface crack growth in Glare, De Koning derived an expression for the stress intensity factor [2]. The derivation stems from the observation of nearly constant crack growth rates for much of the propagation life, which implies a constant stress intensity factor. To achieve this, a second loading system is assumed to travel along with the crack tip. This loading system is fibre bridging.

The physical system is illustrated in Figure 2. The crack opening loads near the crack tip are represented by γS , where S is the remote applied load, and γ is a load transfer coefficient. These loads operate over a process zone defined as $\delta(S/\bar{\sigma})^2$. δ is a characteristic length parameter that depends on the metal sheet thickness, t , only. The correlation between δ and t is ϵ . The yield parameter, $\bar{\sigma}$, is analogous to the yield limit of metals used to determine plastic zone sizes. This parameter is considered to be a material constant of the prepreg in the laminate.

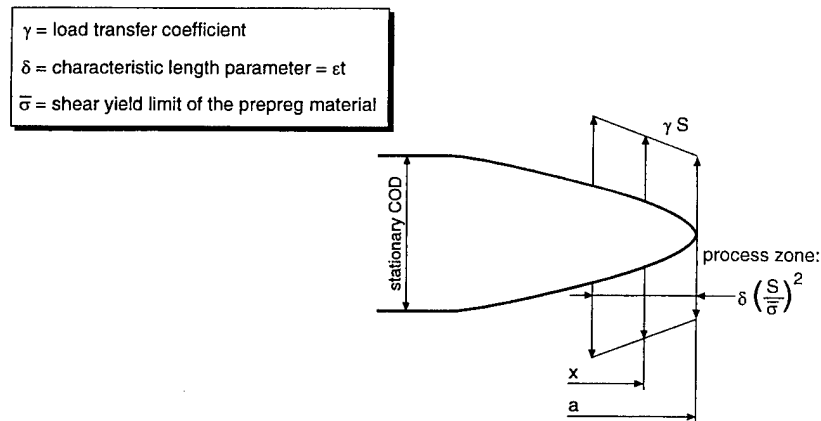


Figure 2: Local stress system near the crack tip [2].

Using this system for a centrally cracked specimen, the stress intensity can be found following Paris & Tada [3]:

$$K = \frac{4}{\sqrt{2\pi}} \left(\frac{\gamma\sqrt{\epsilon}}{\bar{\sigma}} \right) f\left(\frac{a}{w}\right) S^2 \sqrt{t} \quad (2-1)$$

where $f(a/w)$ is a geometry correction factor. Evaluating the system under maximum applied stress, a value for K_{\max} is found. Inserting this into the empirical Paris crack growth law yields:

$$\frac{da}{dN} = C_1 (1 - R^2)^n \left[\frac{4}{\sqrt{2\pi}} \left(\frac{\gamma\sqrt{\epsilon}}{\bar{\sigma}} \right) f\left(\frac{a}{w}\right) S_{\max}^2 \sqrt{t} \right]^n \quad (2-2)$$

A distinction is not made between C_1 and $(\gamma\sqrt{\epsilon}/\bar{\sigma})$ for Glare, rather, C_1 is assumed to be that of the metal ply, 2024-T3 aluminum. The remaining parameters are grouped into one term, and determined by fitting to da/dN versus S_{max} curves.

Homan [4] suggested applying the De Koning model to subsurface crack growth. Two adjustments are required to the model. The first accounts for the thickness term in Equation 2.2 by considering the thickness of the surface metal layer to be the sum of the thicknesses of all cracked metal layers. The second adjustment accounts for the maximum stress term in the model. When a material is under combined tension and bending, the stresses decrease from the outer surface until the minimum at the neutral line. The actual value of the maximum stress in the cracked layer of interest is needed. For a combined tension bending specimen, this value is found by taking the sum of the maximum applied remote stress and the maximum resulting bending stress for that layer. For each layer the resulting bending stress is found by using the neutral line model as described by Fawaz [5].

3. EXPERIMENTS

One Glare open-hole tension-bending specimen as shown in Figure 3 was tested under constant amplitude at 100 MPa applied load, with $R=0.1$ and the test frequency at 10 Hz. The Glare configuration tested was Glare 4A-4/3-0.4 as described in Table 1.

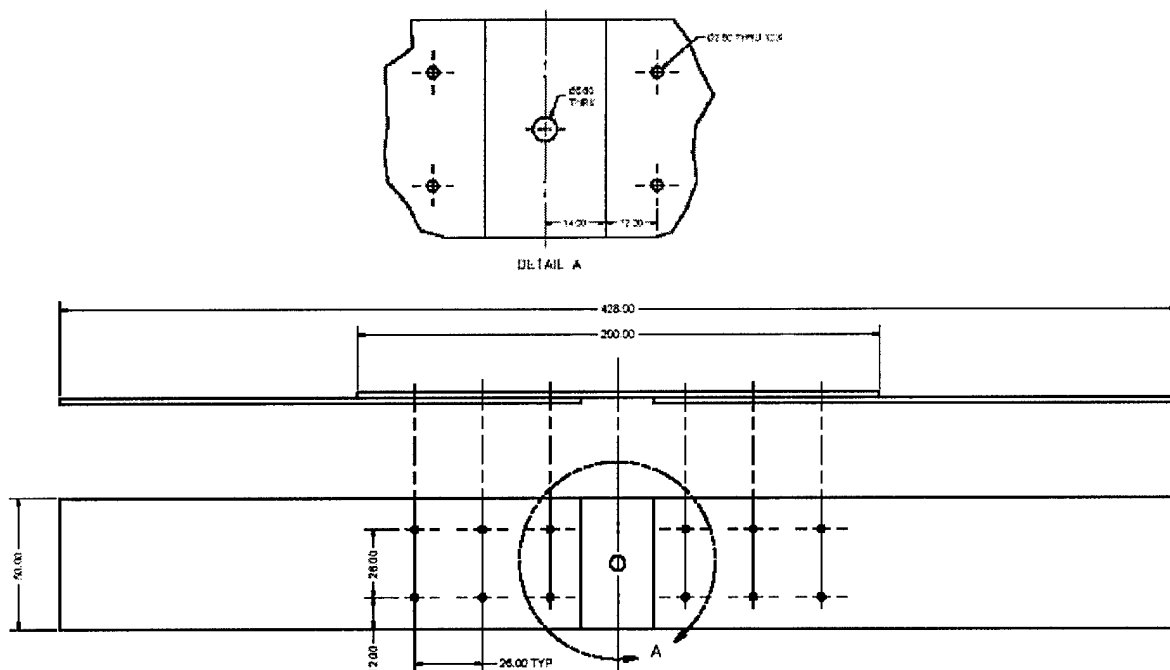


Figure 3: Combined tension bending specimen configuration.

The specimen was tested until a surface crack of 10mm was measured from each side of the open hole. This provided two sets of crack growth data for each layer measured. At regular cycle intervals, surface crack length measurements were performed, and each subsurface aluminium

ply was inspected to determine if a fatigue crack had initiated. An optical endoscope was used to monitor subsurface crack initiation by observing the inner face of the open hole in the specimen as shown in Figure 4. Following the fatigue tests, the sample was destructively inspected. The specimen was placed in an oven at 350 degrees Celsius for four hours to burn away the prepreg between the aluminium plies. This exposed each of the aluminium plies in order to measure the final fatigue crack lengths.

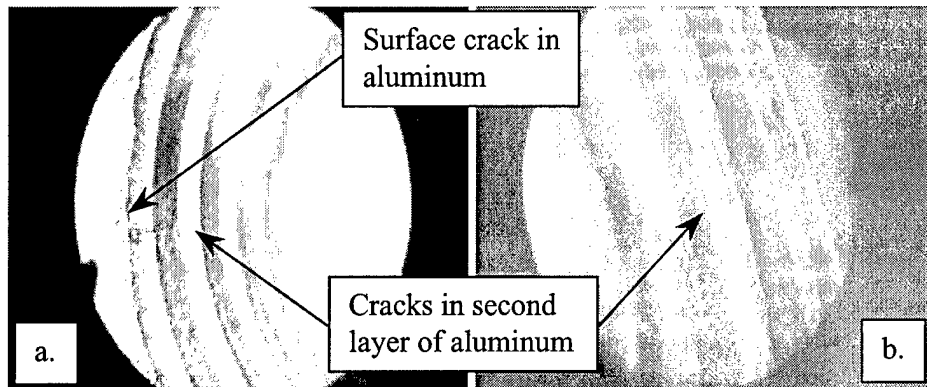


Figure 4: Subsurface cracking through the second layer in specimen at 80 kcycles. Figure-a shows the left side of the hole. Figure-b shows the right.

4. EXPERIMENTAL RESULTS

Crack length versus crack growth rate for the surface layer is shown in Figure 5, with the analytical model superimposed. The model deviates from the experimental data by 8%. As the model was derived to predict surface crack growth, this good correlation is not surprising.

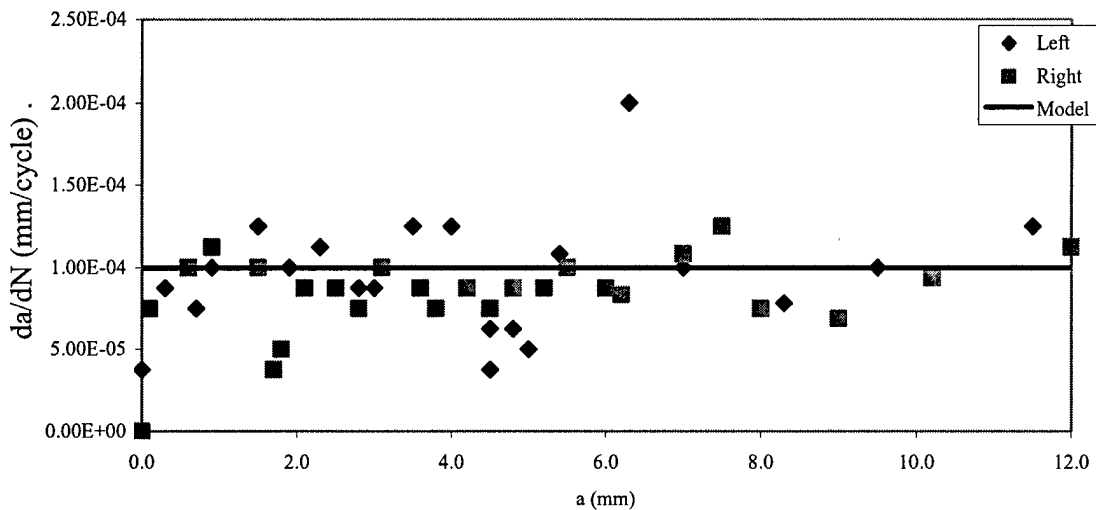


Figure 5: Surface crack a v. da/dN for Glare 4A-3/4-0.4 specimen subjected to combined tension and bending. $\sigma_{max} = 146$ MPa, $\sigma_{app} = 80$ MPa, $R = 0.1$, $(\gamma\sqrt{\epsilon}/\bar{\sigma}) = 0.0139$.

Crack growth for the individual layers is shown in Figure 6, with the analytical models superimposed. For the subsurface cracks we only have the crack initiation cycles and the crack

length at the end of the test, but as both points are relatively far apart they give a good indication of the experimental crack growth. The number of cycles to crack initiation for the model at each layer was assumed to be the average of the numbers of cycles to crack initiation found from the test data. The agreement between model and experiment is not very good. For crack growth in the second layer of aluminum, the model deviates from the experimental data by 29%. For crack growth in the third layer of aluminum, the model deviates from the experimental data by 90%.

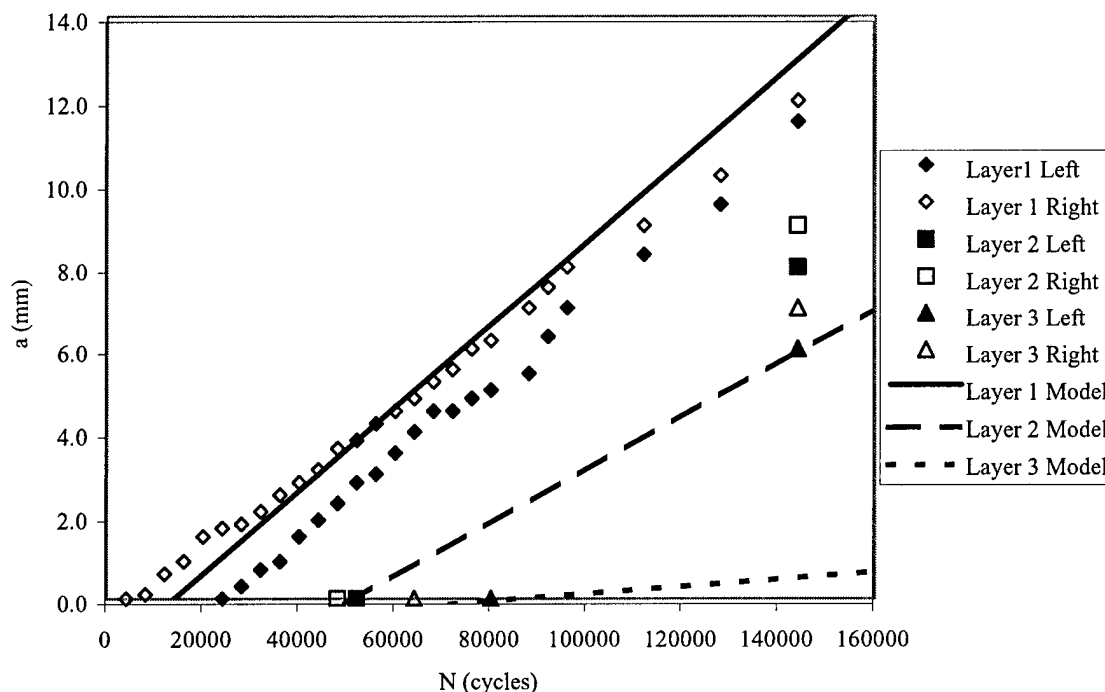


Figure 6: Crack growth by layer for Glare 4A-4/3-0.4 subjected to tension and bending. $\sigma_{app} = 80 \text{ MPa}$, $R = 0.1$. Analytical model included by layer, $(\gamma\sqrt{\epsilon} / \bar{\sigma}) = 0.0139$.

Two possible explanations for the discrepancy are presented. First, the actual stress state may be different from the stress state in the aluminum ply of interest estimated using the neutral line model. Elastic deformation of the prepreg may have allowed the fibres to carry more or less of the applied load than predicted. To bring the model into line with the experimental data, the aluminum plies would need to be carrying more of the load, which implies that the fibres were carrying less. The neutral line model also does not account for cracks in the plies. As fatigue cracks grew in the specimen, the actual stresses in the aluminum plies deviated from the calculated values as the net cross section of the specimen carrying the load decreased. This could account for the higher than predicted crack growth rates in the sample.

A second possible explanation stems from the fact that the model was designed to predict surface cracks in Glare. Modeling subsurface cracks as surface cracks makes significant assumptions regarding the plies of material above the aluminum ply of interest. In this work the assumption was made that all the aluminum plies cracked as one thick ply. This assumption ignores the effects of the fibre bridging taking place on the plies above the subsurface layer. The aluminum

plies above are already cracked, and the fibres are already extended by the crack opening displacement by those cracked aluminum plies. While those fibres are probably not able to significantly aid in the reduction of stress at the new crack tip, the cracked plies as a whole are not acting as a cracked monolithic aluminum ply. The surface crack model, by definition, also does not consider the fact that there are fibres directly above and below the ply of interest. The action of delamination from both sides of the ply may contribute to the inaccuracies of the model for subsurface crack growth as well.

5. DISCUSSION

General trends in De Koning's model have been discussed with regards to experimental data gathered. In addition, a comparison of the model to older data found in literature was conducted to try and gain additional insights.

5.1 Laminated Aluminum. As the prediction of the model to subsurface crack growth in the Glare FML was conservative, it is interesting to question whether the fibre bridging effect has any meaningful impact on subsurface crack growth. To answer that question, crack growth data [6] of an aluminum laminate, not reinforced by fiberglass plies is compared to De Koning's model. The laminate consisted of five layers of aluminum, each 1 mm thick. The test specimens had a surface crack installed and were placed in tension. The crack growth by layer is shown in Figure 7. This data is compared with de Koning's model of a Glare 2B-5/4-0.5 lay up. The model was applied with a crack initiation starting at the same time found from the experiments. This particular grade of Glare was selected for the comparison, as the fibres are parallel to the applied load (see Table 2). This will maximize the influence of fibre bridging on crack growth compared to other grades, and makes it the most relevant grade to compare for this question.

The thickness of the aluminum laminate is 5 mm, and the Glare thickness is 3.5 mm. This difference in thickness results in the thinner Glare model having less stress induced through secondary bending as cracks propagate into the laminate. However, due to the composite makeup of Glare, the aluminum will attract more of the applied stress than the fibres, as the aluminum is more stiff than the prepreg. These two effects may act to balance each other to some extent. This means the comparison between the Glare model and this aluminum laminate is not ideal, but for a first estimate it remains relevant.

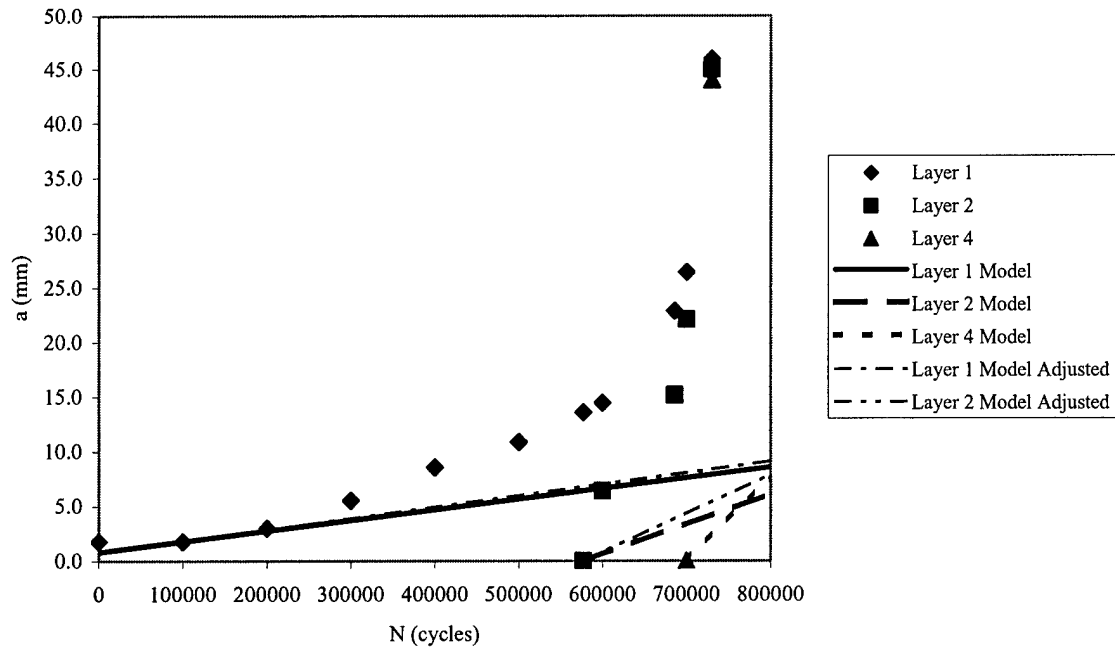


Figure 7: Fatigue crack growth in laminated aluminum compared to predicted crack growth in Glare 2B-5/4-0.5. $\sigma_{app} = 80$ MPa, $R = 0.3$, $(\gamma\sqrt{\epsilon}/\bar{\sigma}) = 0.0117$.

Table 2: Glare 2B-5/4-0.5 stack up sequence.

| Layer | Constituent |
|-------|------------------------------------|
| 1 | 0.5 mm Al2024-T3 L |
| 2 | 0.250 mm 0°/0° Glass Fibre Prepreg |
| 3 | 0.5 mm Al2024-T3 L |
| 4 | 0.250 mm 0°/0° Glass Fibre Prepreg |
| 5 | 0.5 mm Al2024-T3 L |
| 6 | 0.250 mm 0°/0° Glass Fibre Prepreg |
| 3 | 0.5 mm Al2024-T3 L |
| 4 | 0.250 mm 0°/0° Glass Fibre Prepreg |
| 7 | 0.5 mm Al2024-T3 L |

The differences between the actual and predicted crack growth rates are found to be between 90% and 95% for all layers. To try and correct for the conservatism found previously in the model, the predicted crack growth rates are shifted by the amount of error found between the model and the experimental data presented in Section 3. This would increase the analytical model by 8% for the first layer and 29% for the second layer. This can only be done for the first and second layer, as there is no data to compare for the fourth layer. The results are also shown in Figure 7.

The modest increase in crack growth rate predicted by the adjusted model suggests that subsurface crack growth in Glare 2B-5/4-0.5 would be much slower than in laminated aluminum

of the same thickness. This leads to the conclusion that fibre bridging is an important phenomenon in subsurface cracking.

5.2 Riveted lap joint An attempt was made to apply the model to a more realistic configuration to see if the model's tendencies persisted in a more complex environment. Müller [7] monitored crack growth rates in Glare 3-3/2-0.3 specimens configured in a riveted lap joint. The specimen width was 140 mm, and the total length between clampings was 380 mm. Each plate was 220 mm long with an overlap of 60 mm. There were three rivet rows with a rivet spacing of 20 mm. Crack growth rates for Müller's samples are shown in Figure 8 with De Koning's analytical prediction superimposed by layer. The model was applied with a crack initiation starting at the same time found from the experiments. From the data for layer one, a clear transition from faster crack initiation to slower crack propagation can be seen. A transition from slow to faster crack propagation can also be seen later in the fatigue life, until the crack reaches a physical limit - linking up with a crack emanating from an adjacent rivet hole.

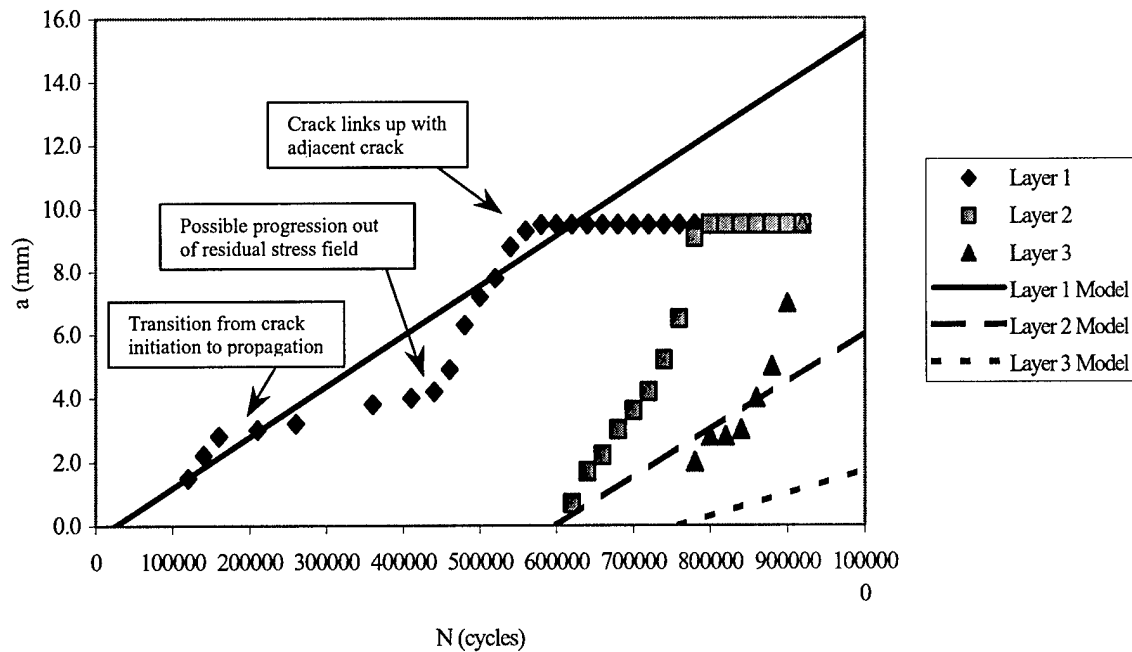


Figure 8: Fatigue crack growth from a rivet hole in a Glare 3-3/2-0.3 lap joint.

$W=140$ mm, $L=380$ mm, 3 rivet rows, Rivet Spacing = 20 mm, $(\gamma\sqrt{\epsilon} / \bar{\sigma}) = 0.0127$.

The riveting process imparts a residual stress field around the hole, which affects the crack growth rate significantly. This may explain the slower than predicted crack propagation after initiation. By looking at a region away from this residual stress field, one would expect to see the crack growth rate align with the analytical model. The crack may have progressed out of the field by 4 mm, which would explain the sharp rise in crack growth up to 9 mm, where the crack linked up with an adjacent crack. Looking at cracks between 4 mm and 9 mm in length, the model is unconservative. This is unexpected for a surface crack, as the model is tuned for this type of crack growth, though the two observed growth rates bracket the model prediction.

For subsurface crack growth, the model persists with a conservative prediction as it did compared to the experimental data. Each group of crack growth data exhibit an "S"-curve of fast, then slow, then fast again crack growth rates. The transitions occurred at roughly the same crack length for each layer, with the exception of the transition to faster crack growth in the third layer.

While the crack growth environment was clearly more complex for this comparison, the general conclusion can be drawn that model's trend was correct for surface crack growth. For subsurface crack growth, the model maintained its unconservatism also present in the current experimental results.

6. CONCLUSIONS

From the experimental data, it can be seen that the model predicted surface crack growth quite well. This is to be expected as the model was tuned for surface cracks. For subsurface crack growth, the model was unconservative. Actual crack growth rates were greater than predicted for both the second and third layers. A misrepresentation of the actual stress state in the subsurface layer by the neutral line model, and a failure to account for fibre layers above the layer of interest may account for the discrepancies.

The experiments conducted were very limited in scope. More data is required to improve on the confidence of the results and conclusions presented here. A degree of confidence can be drawn from the data, however, by looking at the close match between the surface crack growth data and the analytical model. This implies that the subsurface crack growth data is of sufficient quality, and that the tests were conducted properly. The general trend of the model suggests that it is a viable starting point for further analysis.

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