The Influence of Temperature on Crack Growth in Fibre Metal Laminates

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Abstract: A robust crack growth prediction tool has been developed for a class of hybrid skin materials known as Fibre Metal Laminates (FMLs) which has been thoroughly validated for fatigue loading cases at room temperature. This paper provides a brief overview of this predictive model and presents an investigation into its predictive capabilities at various temperatures. Amongst the temperature effects investigated are crack growth rate in the metal layers, delamination growth rate along the metal-fibre interfaces, and residual curing stresses within the laminate. Results from this investigation indicate that the present model accounting for these effects can accurately predict crack growth in FMLs at room temperature and elevated temperature, but is overly conservative for predictions at low temperatures.

1 INTRODUCTION

Aircraft skin panels are exposed to temperatures ranging from 80°C due to extended soak times in the sun in hot and arid climates to -60°C in polar climates and at high altitudes. In order to ensure safety, designers must be able to account for the influence of these conditions on the damage tolerant behaviour of aircraft structures. Without reliable predictive models to carry out this type of analysis, designers must rely on costly experimental tests to demonstrate the safety of their designs.

Fibre Metal Laminates (FMLs) are a relatively new breed of aerospace materials which utilize the customizable layup concept of traditional fibre reinforced composites along with a hybrid material concept. Isotropic metal layers are included in a fibre-reinforced composite layup in order to exploit some of the benefits of metallic and composite materials.

The most common variant of FML currently used in the aerospace industry is the glass fibre-epoxy and aluminum variant known as Glare. Even when considering a single variant where the metal and fibre types are fixed, a wide range of variations in the material can still be present, including metal layer thickness, fibre layer layup, and overall laminate layup. Performing tests on all possible variations in order to characterize the influence of temperature on crack growth performance is undesirable.

Currently, a crack growth model for FMLs exists which has been extensively verified for room temperature crack growth conditions. This paper examines a series of studies that aimed at extending this model to account for the influence of temperature. First, a brief review of the basis for the model will be presented followed by results from the study to extend the model capabilities.

2 FML CRACK GROWTH MODEL

The fatigue crack growth process in FMLs comprises an intricate balance of various damage and load redistribution mechanisms. Fatigue cracks initiate and grow within the individual metal layers while delmainations form and grow between the metal and fibre layers. Crack growth in the metal layers is retarded by the bridging action of the fibre layer while the bridging load carried by the fibre exacerbates delamination growth. The size of the delamination, in turn, determines the bridging load carried by the intact fibre layer. Each of these mechanisms needs to be considered in order to fully capture the crack growth behaviour in FMLs.

Significant research effort has been invested within the Technical University of Delft into modelling the fatigue crack growth phenomenon in FMLs [1-5]. These efforts have produced a robust model for crack growth which has been thoroughly validated for various FML configurations at room temperature conditions. The basis for this model will be briefly described here. Further details can be found in other publications [1, 2].

2.1 Metallic Crack Growth

Crack growth within the metallic layers of an FML is treated using a standard linear-elastic fracture mechanics approach. Crack growth behaviour is predicted using a Paris Law relation such that:

$$\frac{da}{dN} = C_{cg}\left(K_{eff}\right)^{n_{cg}} \tag{1}$$

where a is the crack length, N is the number of cycles, ΔK_{eff} is the Mode I stress intensity factor and C_{cg} and n_{cg} are the Paris Law coefficients describing the crack growth behaviour. ΔK_{eff} is calculated using the Schijve correction [6]:

$$\Delta K_{eff} = \left(0.55 + 0.33R + 0.12R^2\right)\left(1-R\right)K_{\max} \tag{2}$$

$K_{\max}$ is comprised of two components: the stress intensity factor due to far field stress (including residual stress) and the reduction in stress intensity factor due to fibre bridging. Determination of the second component will be further discussed in Section 2.3.

2.2 Delamination Growth

Growth of delaminations between the metallic and fibre layers is, similar to crack growth in the metal layers, treated using a linear elastic fracture mechanics approach. The delamination resistance of the interface is characterized with a series of experimental tests resulting in a Paris Law relationship for delamination growth rate in terms of strain energy release rate. Only the mode II strain energy release rate is considered, which ahs been found to be sufficient for crack growth predictions in FMLs [4]. Thus:

$$\frac{db}{dN} = C_d \left(\sqrt{G_{II_{\max}}} - \sqrt{G_{II_{\min}}} \right)^{n_d} \tag{3}$$

where b is the delamination length, N is the number of cycles, G_{II} is the mode II strain energy release rate, and C_d and n_d are the Paris Law coefficients describing the interface behaviour.

The formulation of the strain energy release rate range used in eq. (3) requires some explanation. Typically, delamination growth has been characterized using the maximum strain energy release rate, $G_{\max}$, or the arithmetic difference between the maximum and minimum strain energy release rates, $\Delta G = G_{\max} - G_{\min}$. Both of these formulations, however, fail to accurately represent the applied stress range. If the rules of superposition for strain energy release rate are examined for a single mode of loading, than G is defined as [7]:

$$G_{II} = \left[\sqrt{G_{II(1)}} + \sqrt{G_{II(2)}} + \sqrt{G_{II(3)}} + \cdots \right]^2 \tag{4}$$

Thus the strain energy release rate range should be defined as the difference of the roots of the maximum and minimum strain energy release rates squared. This is precisely the formulation used in eq. (3), except the squared term is included within the Paris Law coefficient, n_d. This formulation also has the added benefit that it removes the effects of residual stress from the delamination growth analysis as the same residual stresses are present at the maximum and minimum load, and are thus cancelled out when taking the difference.

2.3 Crack Bridging

Crack growth in the metal layers and delamination growth between the metal and fibre layers influence each other through the crack bridging process. This influence can be visualized by considering an infinitesimal width of an FML laminate as shown in Figure 1. A bridging stress (S_{br}) is transferred from the cracked metal layers to the intact fibre layers. The bridging stress acts to close the crack in the metal layers and elongate the intact fibre layers.

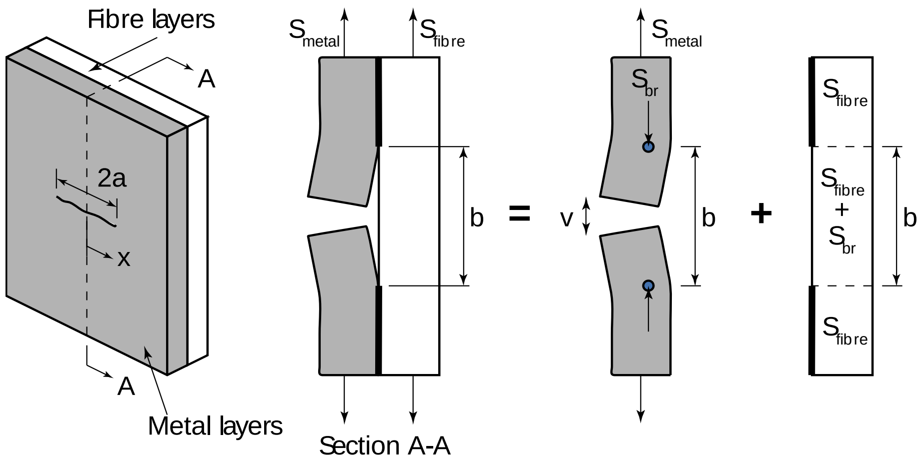

Figure 1: Infinitesimal section of cracked FML showing division of bridging load effects on cracked metal and intact fibre layers (only on metal and one fibre layer shown for clarity).

The amount of crack opening, v, can then be related to both the metal and fibre layers due to displacement compatibility along the delamination front. Thus, over the delamination length, b, the crack opening is given by:

$$v = v_{\infty} - v_{br} = \delta_f + \delta_{pp} \tag{5}$$

where v_{∞} and v_{br} are the far field and bridging stress contributions to crack opening in the metal layer, δ_f is the elongation of the fibre layer over the delamination length and δ_{pp} is the shear deformation of the fibre layer. Further details on determining these terms can be found in [1, 2]. Using this compatibility equation, the bridging stress at any point along the delamination front can be solved for. Once the bridging stress distribution is known, a crack tip stress intensity reduction factor (K_{br}) can be determined. Similarly, the strain energy release rate can be calculated, including the bridging stress component. Thus, the crack growth and delamination growth analysis can be updated to include the effects of crack bridging, such that:

$$\begin{aligned} K &= K_{\infty} - K_{br} \\ G_{II} &= f\left(S_1, S_2, S_{br}\right) \end{aligned} \tag{6}$$

2.4 Model Implementation

Implementing the above described analyses into a single FML crack growth model requires an assumed initial crack length and delamination. Based on these initial conditions, the bridging stress distribution along the crack length can be calculated and used to determine the stress intensity reduction factor due to bridging and the strain energy release rate along the delamination front. To simplify the delamination growth analysis, the delamination is discretized into several strips within which 1-dimensional delamination growth behaviour is assumed. Thus, the bridging stress distribution is transformed to point loads acting on each of these delamination zones, which simplifies determination of G and K_{br} within the analysis. The delamination front is assumed to be fixed to the crack tip and more delamination zones are added as the crack grows. A more extensive description of the model implementation can be found in [1, 2].

3 INFLUENCE OF TEMPERATURE

In order to model crack growth in FMLs at high and low temperatures, the effects of temperature on the various mechanisms which the crack growth model comprise of must be established. Temperature can have a wide range of influences on a material, affecting numerous mechanical properties such as stiffness, fatigue resistance, and ductility. For this particular study, only the influence of temperature on crack growth behaviour in the metal layers, delamination growth between the metal and fibre layers, and residual stresses within the FML has been considered [8]. Each of these factors will be examined and their treatment in the FML crack growth model described.

3.1 Metal Crack Growth Behaviour

The crack growth behaviour of the metal layers of an FML is described within the FML crack growth model using a Paris Law relation. The various coefficients of the Paris Law relation are known to vary with temperature as well as material thickness. Despite the literature being full of numerous studies which examine the fatigue crack growth resistance of aluminum alloys as a function of temperature, few examine the thin sheet thicknesses that are used in FMLs.

Motivated by the need for temperature dependant fatigue crack growth data for the thin gauge aluminum sheets used in FMLs, an experimental study was undertaken [8]. Fatigue tests on thin 2024-T3 Centre Crack Tension (CCT) specimens were carried out at -30°C, 20°C, and 70°C. Crack growth rates were measured and plotted against K_{eff} ($K_{eff} = (0.55 + 0.33R + 0.12R^2)(1 - \mathrm{R})K_{\max}$), as shown in Figure 2. A reference curve for the room temperature crack growth behaviour obtained from [9] was also plotted.

Results from this study indicated that, relative to the reference room temperature behaviour, crack growth was unaffected by elevated temperature while an increase in crack growth resistance was exhibited at lower temperatures. Based on these results, a new set of Paris Law coefficients were obtained for the low temperature behaviour while the room temperature coefficients were deemed to be representative of both room and elevated temperatures.

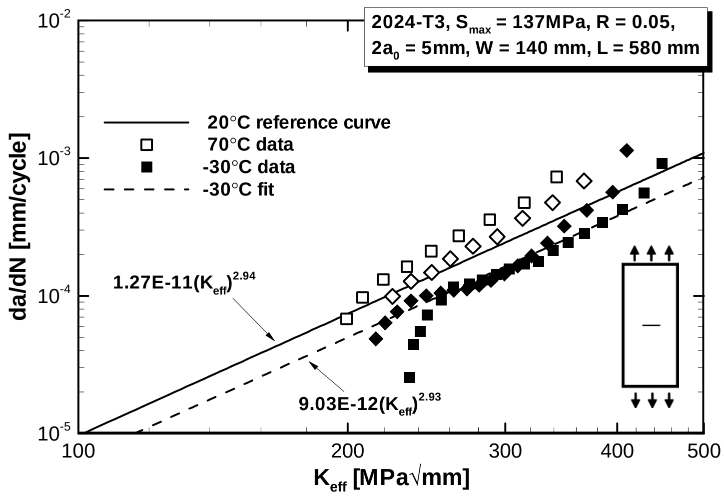

Figure 2: Influence of temperature on crack growth rate in thin 2024-T3 sheet (data from [8, 9]).

3.2 Delamination Growth Behaviour

Similar to crack growth, the delamination growth behaviour for the metal-prepreg interfaces in an FML is described in the FML crack growth model using a Paris Law relation. In order to predict the influence of temperature on FML crack growth, the effects of temperature on the delamination Paris Law coefficients is needed.

The influence of temperature on delamination growth has been investigated using FML tension fatigue specimens containing a fully cracked central metal layer [10, 11]. Details regarding the experimental approach can be found in [4]. Results obtained for tests carried out at -40°C, 20°C, and 70°C are shown in Figure 3, plotted against the Mode II strain energy release rate range.

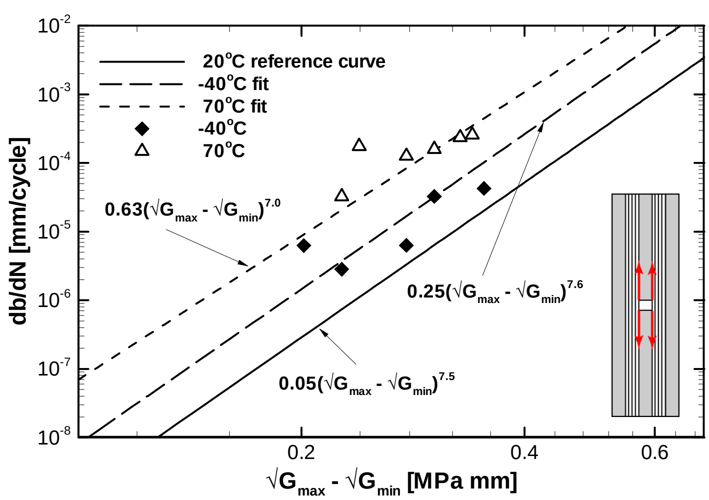

Figure 3: Influence of temperature on delamination growth rate along 2024-T3/glass fibre epoxy interface (data from [1, 4, 10, 11]).

Contrary to crack growth in the metal layers, both elevated and low temperatures exhibited an influence on delamination growth. In both cases, the resistance to delamination growth decreased. The influence at elevated temperatures was observed to be more pronounced. From these test results, Paris Law coefficients can be obtained for FML crack growth predictions.

3.3 Residual Stress

The final influence of temperature to be considered is its effect on residual curing stress. Due to the mismatch in thermal coefficient of expansion between the metal and fibre layers in an FML, a residual stress state forms which is proportional to the difference in curing and operating temperature. Due to the formulation of the strain energy release rate range used to characterize delamination growth, this residual stress can be ignored for the delamination growth analysis. The residual stress in the metallic layers, however, has a significant influence on crack growth.

Determination of the residual stress is carried out using classical laminate theory. Details will not be provided here, but can be found in [12]. For the most common FML variant known as Glare (glass fibre reinforced aluminum), the lower stiffness of the fibre layers relative to the aluminum layers and the mismatch in thermal coefficient of expansion result in tensile residual stresses in the metallic layers for temperatures below the curing temperature (120°C). The magnitude of this residual tensile stress increases as the operating temperature drops; thus elevated temperatures are expected to have a favourable effect while lower temperatures result in increased residual tensile stresses in the aluminum layers.

4 MODEL VERIFICATION

Using the temperature dependent delamination growth, metal crack growth, and residual stress behaviour described in the previous section, FML crack growth behaviour can be predicted using the crack growth model described in Section 2. To verify the predictive capabilities of this model, a series of fatigue tests were carried out.

4.1 Verification Test

Fatigue tests were carried out on Centre Crack Tension (CCT) specimens constructed of the FML variant known as Glare. A 6/5 layup consisting of 6 aluminum and 5 cross-ply glass fibre epoxy layers was used (Glare3-6/5-0.4). Cracking was initiated by placing a 5 mm saw cut in the centre of each 140 x 580 mm specimen. Tests were performed at constant amplitude stress levels of 70 and 120 MPa (R = 0.05), and at temperatures of -40°C, 20°C, and 70°C. Crack growth measurements were made using the potential drop method [13].

4.2 Verification Results

Crack growth results for each of the fatigue test cases along with predictions from the FML crack growth model, modified to account for temperature dependent behaviour, are shown in Figure 4. Excellent agreement between the experimental results and predictions were obtained for the 20°C and 70°C cases. The predictive model was, however, unable to capture the observed crack growth behaviour for the -40°C case.

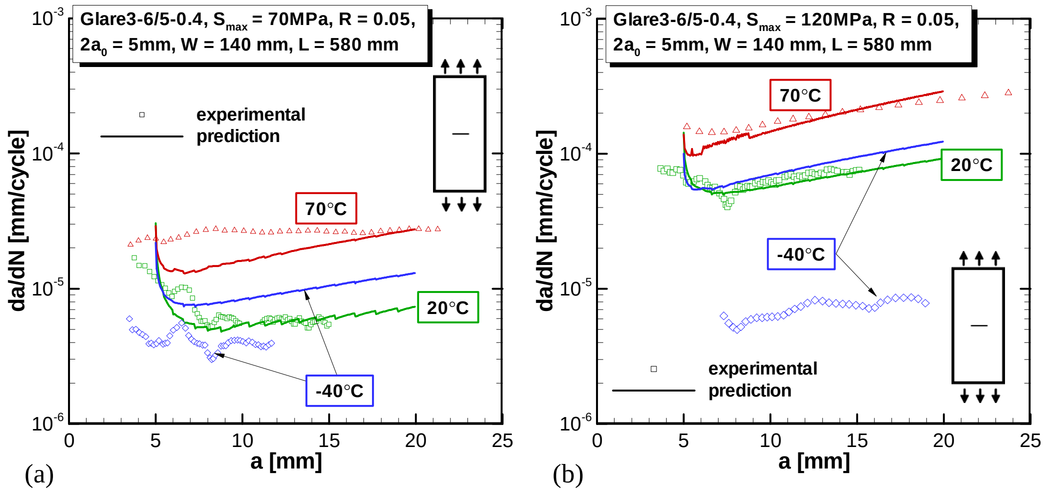

Figure 4: Comparison of experimental and predicted crack growth rates in Glare at various temperatures; (a) S_{max} = 70 MPa, (b) S_{max} = 120 MPa.

5 DISCUSSION

Based on the temperature dependent mechanisms described in Section 3, the predictions made with the modified FML crack growth model agree with the expected temperature dependent behaviour. The crack growth rate predictions for 70°C are higher than the 20°C predictions due to the reduced delamination growth resistance at the elevated temperature. A larger delamination size implies a larger degree of crack opening (as per eq. (5)), and thus a larger crack tip stress intensity factor. A small reduction in stress intensity factor is also expected due to the lower residual tensile stress state in the aluminum layers at 70°C; however, this reduction is overshadowed by the effect of the delamination size.

The crack growth predictions for the -40°C case are also higher than the 20°C case. The disparity in the predictions, however, is much less than observed between the 70°C and 20°C predictions. Similar to the 70°C case, part of this behaviour can be attributed to the lower delamination growth resistance. The other contributing factor is the higher residual tensile curing stress present in the aluminum layers at -40°C. Both of these factors are countered by the increased crack growth resistance of the aluminum layers at low temperature.

Although the predicted crack growth behaviour seems sensible given the temperature dependent mechanisms considered, results from the experimental verification program indicate some remaining issues. The 70°C and 20°C predictions agree very well with the experimental results and will not be further discussed. Prediction results for -40°C case do not agree with experimental results, indicating that some additional mechanism is present which influences the low temperature behaviour. From a practical standpoint, this difference is of little concern as the low temperature crack growth resistance is higher than at room temperature, and is thus not a critical case for design. Use of room temperature crack growth behaviour would simplify the analysis and result in a conservative design. From a scientific standpoint, it is desirable to understand the reasoning for this difference.

Several additional factors could be contributing to the lower crack growth rates observed in the experiments conducted at -40°C. Material stiffness is known to vary with temperature, and if the relative stiffness of the fibre and metal layers increased at low temperatures, load redistribution could result in lower stresses in the metal layers. Additionally, an increase in shear stiffness of the fibre layer at low temperatures could reduce the shear deformation term in eq. (5), thus reducing crack opening and ultimately crack growth rate. Although these are potential explanations for the disparity in the low temperature predictions and experimental results, further research into this area is still needed.

6 CONCLUSIONS

This paper presented an overview of a robust FML crack growth prediction tool as well as the results of a study aimed at extending the capabilities of the model to account for temperature dependent crack growth behaviour. Based on the results of this study, the following conclusions can be made:

- Inclusion, within the current FML crack growth prediction tool, of the temperature dependent metallic crack growth, delamination growth, and residual curing stress behaviour of the constituent materials in an FML are sufficient for predicting crack growth behaviour at elevated temperatures.
- These inclusions are insufficient for predicting the low temperature crack growth behaviour. Further research is needed to establish which additional factors need to be considered.
- Despite the lack of accurate predictive capabilities for low temperature crack growth in FMLs, treatment of such low temperature conditions as room temperature conditions results in a conservative prediction of performance which is suitable for design purposes.

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