DELAMINATION GROWTH RATE AT LOW AND ELEVATED TEMPERATURES IN GLARE

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Abstract

Delamination tests have been performed on Glare specimens at low and elevated temperatures. A Paris type relation has been obtained by relating the recorded delamination growth rates to the Energy Release Rate calculated for the applied specimen geometry. The dependency of the obtained relations on the environmental temperature has been analyzed and described by a simple empirical relation.

1 Introduction

Glass Reinforced aluminum (Glare) is the successor of Aramid Aluminum Laminate (ARALL). This second generation Fibre Metal Laminate (FML) was also developed at Delft University of Technology (TU Delft) in The Netherlands and is currently applied in the Airbus A380.
Glare combines the mechanical properties of 2024-T3 aluminum and S2-glass fibers. The glass fibers are impregnated in a FM94 epoxy system. Glare is cured into a final product in an autoclave at 120 °C and a maximum pressure of 6 bar [1].
Glare is applicable in many lay-ups, depending on the desired mechanical characteristics in the application. The main variable in the lay-up is the orientation of the pre-impregnated glass fibers (prepreg). These fibers can be oriented in different angels with respect to the loading direction. The longitudinal direction (0°), traverse rolling direction (90°) are most common and the third option is the 45° lay-up. The aluminum sheet thickness can also vary to obtain the desired lay-up.
A coding system was developed to easily designate the applied Glare grade. This coding system designates the aluminum sheet thickness, the aluminum alloy and the prepreg orientation of each fiber layer. An entire overview of Glare types can be found in [1].

Many characteristics of Glare have been investigated with experiments to certify Glare as an aerospace material and to make it applicable for the A380. Despite the fact that Glare has reached its technology readiness, not all characteristics have been studied thoroughly, to fully understand its behavior in any given situation.

TU Delft is conducting research on the fatigue behavior of Glare. This paper presents the results of the delamination growth investigation at different temperatures regarding the fatigue crack growth behavior of Glare.

2 Theoretical background

The fatigue crack growth behavior of a Fiber Metal Laminate is influenced by several factors that are related to the composition of the laminate and the mechanical properties of the constituents. The most important factors are the fiber bridging and the delamination growth.

2.1 Fiber bridging

Similar to monolithic aluminum, cracks can initiate and propagate from surface

scratches or rivet holes under fatigue loading. The glass fibers, however, are insensitive to the fatigue loading, which is the key benefit of this material regarding crack propagation. The prepreg transfers loads over the crack, decreasing the stress intensity at the crack tip and reducing the crack growth rate, see Figure 1. The crack growth life of Glare is significantly extended compared to monolithic aluminum. Because, the crack bridging is related to the crack opening, the loads are initially mainly transferred through the aluminum sheets until a certain crack opening is reached.

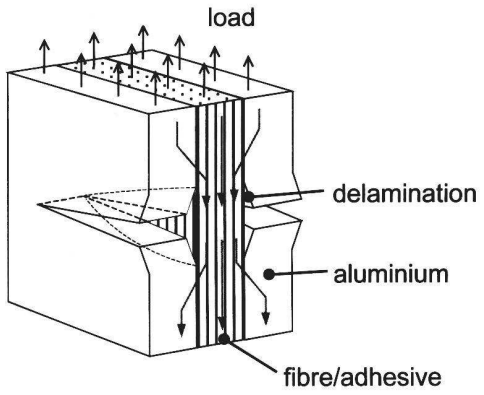

Figure 1. Crack bridging

2.2 Delamination

In Glare, separation of the fiber-adhesive layer from the aluminum layers (delamination) occurs at the location of the fatigue crack in the aluminum layers.

The most commonly used method to describe delamination growth is the Energy Release Rate approach which can be used when the delamination is considered two dimensional. This method is based on Linear Elastic Fracture Mechanics [2].

The Energy Release Rate for delamination (G_d) for the configuration illustrated in Figure 2 can be determined with [3,4]

$$G_d = \frac{\sigma_{lam}^2}{2jE_{al}}\left[\gamma^2(n_{al}-1)t_{al} - \lambda^2 n_{al} + \frac{E_{f,0}}{E_{al}} n_{f,0} t_{f,0}(\gamma^2-\lambda^2) + \frac{E_{f,90}}{E_{al}} n_{f,90} t_{f,90}(\gamma^2-\lambda^2)\right] \quad (1)$$

where

$$\gamma = \frac{t_{lam}}{(n_{al}-1)t_{al} + \frac{E_{f,0}}{E_{al}} n_{f,0} t_{f,0} + \frac{E_{f,90}}{E_{al}} n_{f,90} t_{f,90}} \quad (2)$$

and,

$$\lambda = \frac{t_{lam}}{n_{al} t_{al} + \frac{E_{f,0}}{E_{al}} n_{f,0} t_{f,0} + \frac{E_{f,90}}{E_{al}} n_{f,90} t_{f,90}} \quad (3)$$

with t the layer thickness, n the number of layers and E the Young's modulus. De subscripts *al*, *f,0* and *f,90* denote the aluminum, the fiber layers in loading and perpendicular to the loading direction respectively.

With the Energy Release Rate, the delamination growth rate can be determined with equation 4, where C_d and n_d are constants which are determined from test results [5].

$$\frac{db}{dN} = C_d\left(\sqrt{G_{d,\max}} - k\sqrt{G_{d,\min}}\right)^{n_d} \quad (4)$$

To decrease the crack growth rate in Glare, the delamination growth rate can be reduced, using an adhesive system with higher delamination resistance. However, when the delamination growth rate is reduced too much, the fibers have to carry very high loads, which could induce fiber failure and thus ineffective fiber bridging. This will result in a faster crack growth rate.

2.3 Stresses in Glare

Glare is a laminate, which means that the magnitude of the stresses should be calculated with the Classical Laminate Theory based on the applied laminate stresses. In addition to the effect of different stiffnesses of the individual

layers, the actual stress in each layer is also influenced by the presence of curing induced residual stresses. As result of the different coefficients of thermal expansion the aluminum layers want to shrink more than the fiber layers during cooling down, which gives tensile residual stresses in the aluminum layers and compressive residual stresses in the fiber layers. The stress intensity factor K at the crack tip in the aluminum layers of Glare can be calculated with

$$K_{tip} = K_{al} - K_{br} \tag{5}$$

where K_{al} is based on the actual aluminum stresses and K_{br} describes the bridging effect of the intact fiber layers. The stress intensity factor K_{al} can thus be written as

$$K_{al} = C \cdot \sigma_{al} \cdot \sqrt{\pi \cdot a} \tag{6}$$

The factor C in equation 6 is the correction factor for the geometry, such as Fedderson or Dixon, which can be found in the literature.

The stress intensity factor K_{br} is based on the bridging stresses acting on the delamination contour. The cyclic bridging stress induces cyclic shear stress at the aluminum/fiber interface, which is an important delamination initiator in Glare. When cyclic stresses are applied on Glare, the shear stresses at the interface between the aluminum and prepreg cause the prepreg to deform and the delamination to growth between the layers.

3 Experimental program

Fatigue cracks are an important damage factor in aircraft materials and in order to choose the right material for an aircraft application, all fatigue characteristics have to be known. This means that the fatigue behavior of Glare had to be tested and understood before application in an aircraft is possible.

An analytical crack growth model has been developed [3] to predict the crack growth in Glare. To be able to validate the model, experiments have been conducted, consisting of crack growth tests and delamination tests. This paper presents similar delamination tests but performed at different temperature levels. It also explains the way the results have been implemented in the available model.

3.1 Test environment

The environmental situations in which aircraft operate, gives a good definition of the temperature range in which tests have to be conducted. The operating temperature range of aircraft varies between 80°C and -55°C. Fatigue tests thus have to be conducted between these temperatures.

3.2 Test specimens

For the delamination experiments Glare2A-3/2-0.3 specimens have been tested with fibers solely in loading direction. The specimens were manufactured with the middle aluminum layer containing an artificial crack to initiate the delamination growth, see figure 2. The nominal thickness of all the specimens was 1.4 mm.

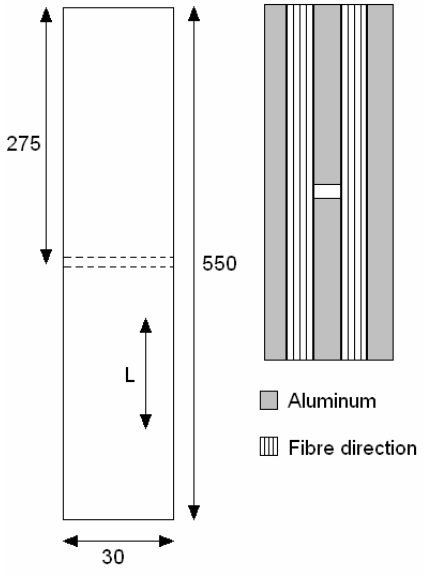

Figure 2: Specimen dimensions

The specimens were coated on the side with a thin iso-propanol thinned layer of tippex (correction fluid) to make the delaminations visible. This thin layer of tippex is a very brittle material that cracks along with the delamination. Because the delaminations have an utmost length of a few millimeters and are hardly visible with the naked eye, the thin tippex layer, combined with a CCD digital camera, made it possible to observe the delaminations.

The specimens were provided with small taps at both specimen ends to avoid crack initiation in the aluminum layers induced by the testing machine's clamps.

The mechanical properties of the Glare constituents are given in tables 1 and 2.

Fibre orientation	0	[°]
Thickness	0.133	[mm]
Young's Modulus	48900	[MPa]
Shear modulus (xy-direction)	5550	[MPa]
Poisson's Ratio, xy	0.33	[-]
Poisson's Ratio, yx	0.0371	[-]
Thermal Expansion Coefficient	$6.1 \cdot 10^{-6}$	[1/°C]
Curing temperature	120	[°C]

Table 1: Prepreg mechanical properties

Thickness	0.3	[mm]
Young's Modulus	72400	[MPa]
Shear Modulus	27600	[MPa]
Poisson's Ratio	0.33	[-]
Thermal Expansion Coefficient	$22 \cdot 10^{-6}$	[1/°C]

Table 2: Aluminum mechanical properties

3.3 Test setup

The specimens were tested on a 100 kN computer controlled fatigue machine at different load levels and at different temperatures. For elevated temperatures, an insulated infrared heat chamber was positioned around the specimen [6]. With the use of a thermocouple placed on the specimen at the location of the delamination an equal and steady temperature was maintained throughout the tests. For low temperatures, an isolation chamber was positioned around the test setup. The air in the isolation chamber was cooled down with a refrigerator using liquid nitrogen supply. At room temperature (RT, approximately 23 °C), there were no additional features added to the test setup.

For each measurement, the chamber was opened and the delamination length was measured, from the artificial crack to the delamination tip, with the measuring system of the CCD camera (figure 3).

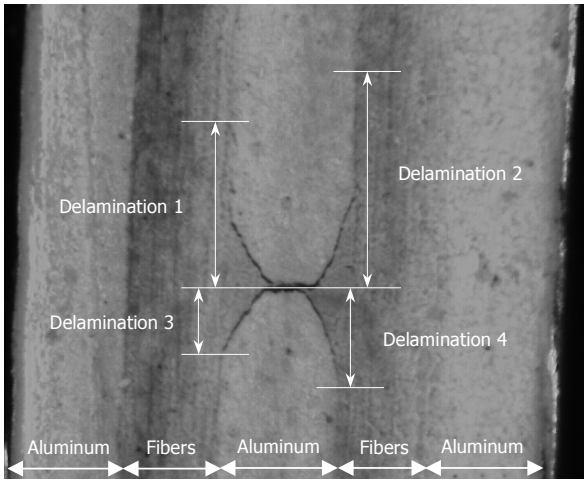

Figure 3: Delaminations in Glare specimen

3.4 Test parameters

The test parameters were carefully chosen since there was a limited amount of specimens available. All test specimens for the elevated temperature tests and the low temperature tests were manufactured out of two sheets of Glare to minimize the difference in mechanical properties. All specimens were tested with a stress ratio of R=0.05 at a frequency of 10 Hz. This way all specimens were subjected to a tensile stress. The specimens were subjected to a load range between 160 MPa and 260 MPa and temperatures of -55°C, -40°C, -20°C, RT, 40°C and 70°C.

Each specimen was tested, at one temperature level and, if possible, at several load levels to obtain enough reliable data for each temperature and load level from the limited amount of specimen.

4 Analysis of test results

4.1 Delamination tests

All test data has been documented and processed in a data file. When the number of cycles of a specimen at a specific load level is plotted versus the delamination length, the delamination growth rate is represented by the slope of the graph (figure 4).

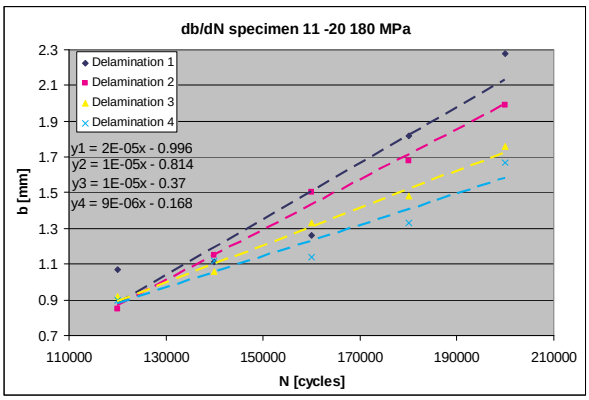

Figure 4: Delamination growth curves

The delamination growth rate was then plotted on a logarithmic scale against the corresponding calculated Energy Release Rate. The equation derived from the trend line of this graph (figure 5) gives the values of the C_d and n_d in equation 4. The obtained values are presented in table 4.

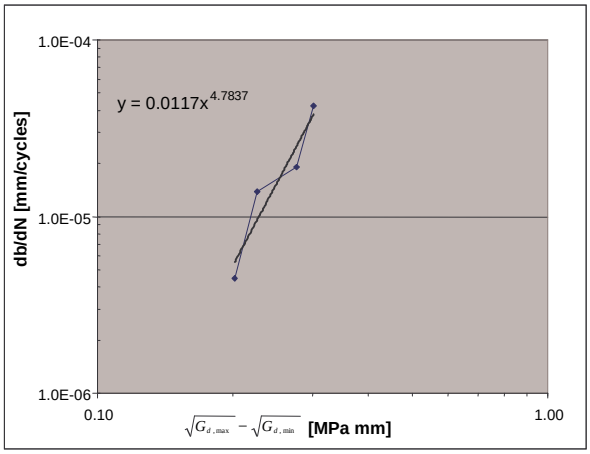

Figure 5: C_d and n_d values derived from trend line for the temperature of -20°C

T	C_d	n_d
70°C	0.272	6.304
40°C	0.141	7.997
Room temperature	0.137	7.414
-20 °C	0.012	4.784
-40 °C	0.002	3.860
-55 °C	0.252	7.561

Table 4: Uncorrected C_d and n_d values

From the results, it was observed that the high temperatures, to which the specimens were exposed, caused a degradation of the delamination behavior of the material. To obtain a more generic description of the delamination behavior it is assumed that all the Paris relations, of which one is shown in figure 5 has the same slope. To determine the n_d value for Glare, the average value of all specimens has been taken. As a consequence, the C_d values for each tested specimen has been corrected accordingly

When the correction method is applied on the data, the following C_d and n_d values are generated (see table 5):

T	C_d	n_d
70 °C	0.630	6.36
40 °C	0.037	6.36
23 °C	0.031	6.36
21 °C	0.020	6.36
-20 °C	0.060	6.36
-40 °C	0.033	6.36
-55 °C	0.025	6.36

Table 5: Corrected C_d and n_d values

The new C_d values give the opportunity to derive a relation between the C_d and temperature. This means, that it is possible to calculate the delamination growth rate belonging to a specific temperature. The values for C_d versus the applied temperature are given in Figure 6.

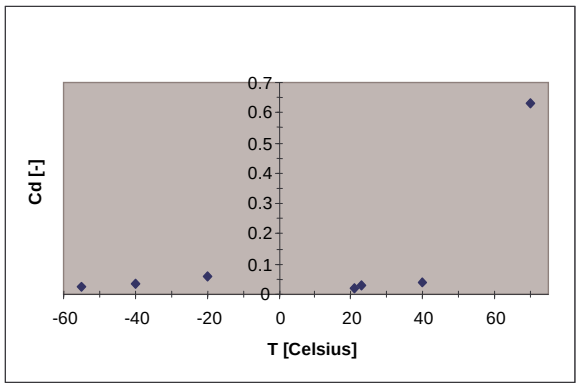

Figure 6: C_d as function of T for the tested temperatures

Figure 6 suggests that the value of C_d is approximately constant over the range of low temperatures and only increases with increasing temperature. Because only the data point at 70 °C deviates significantly, this figure might also be interpreted as if C_d is independent of the environmental temperature except for elevated temperatures close to the glass transition temperature of the adhesive system.

Currently it is assumed that for elevated temperatures C_d can be written as function of the temperature with

$$C_d(T) = c_1 T^{c_2} + C_{d,RT} \quad (7)$$

while C_d for temperatures below room temperature is equal to $C_{d,RT}$.

4.2 Crack growth model

The analytical model to predict crack growth in Glare has been validated before with crack growth tests on Glare at room temperature [3]. Since fatigue crack growth tests on CCT specimen at low and elevated temperatures were also performed, the model could also be validated with the delamination test data at low and elevated temperatures.

The C_d and n_d values have been implemented as input in the model to verify the accuracy of the model (figures 7, 8 and 9). The predictions are compared with crack growth tests of Glare at three different temperature levels: -40°C, 20°C and 70°C.

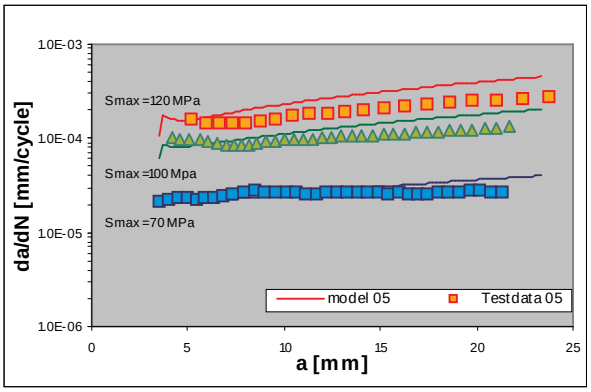

Figure7: Prediction and measurement crack growth data at three load levels, 70 ℃

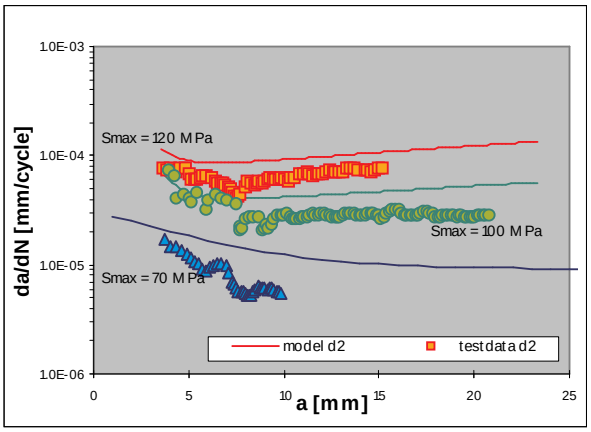

Figure 8: Prediction and measurement crack growth data at three load levels, 20 ℃

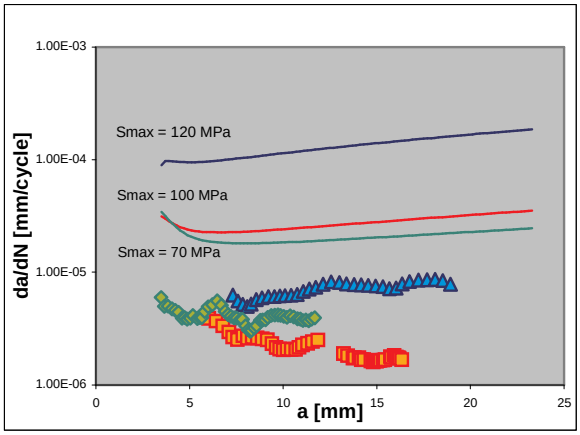

Figure 9: Prediction and data of crack growth measurements at three load levels, -40 ℃

It is clear that the test data and the model predictions correlate quite well for elevated temperatures. The correlation between prediction and test data at 20°C is less, but still within the acceptable limits. However, the comparison between prediction and test data for -40°C shows a significant mismatch. Figure 9 seems to indicate that the fatigue behavior of Glare at low temperatures is significant better than calculated with the model including the measured delamination behavior at that temperature. The difference between data and predictions at -40 ºC is such that it cannot be explained by with the applied values for C_d and n_d. Variation of these parameters within reasonable limits did not reproduce the crack growth behavior observed in the tests.

The predictions have shown to be more sensitive to the Paris relation for crack growth in the aluminum layer. For the low temperature range a different crack growth relation has been used compared to room temperature and elevated temperature. The values in the Paris relation for -40°C have been obtained from [6,7] where thin monolithic aluminum sheets have been tested at this temperature level. However, variation of the parameters in this relation even beyond reasonable limit did not produce the crack growth results observed in the tests. This means that the difference in predicted and tested crack growth data cannot be explained with the current model and the input parameters derived from the presented delamination tests.

5 Conclusion and recommendation

Delamination plays an important role in the crack growth process of Glare. For this reason fatigue delamination tests have been conducted on Glare in order to enable prediction of crack growth in Glare at temperature levels different from room temperature. The tests were conducted to obtained delamination input data for the crack growth model that has been developed previously.

From the delamination data, a relation for C_d as function of the temperature has been derived. From the results, it can be concluded that more fatigue tests of Glare are necessary to verify the current C_d-T relation, especially in the range between 40°C and 70°C. The question to be answered is whether the significant increase of the C_d value at 70°C is related to the glass transition temperature or whether a more gradual increase can be found related to temperature increase only.

The implementation of the delamination data in the prediction model indicates that the model is only valid for temperature levels above room temperature. For temperatures lower than room temperature, there is a mismatch between test data and crack growth prediction. Although the model can be used as the predictions give very conservative results, it is recommended to further investigate this mismatch at low temperatures.

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