FIBRE METAL LAMINATES AND VARIABLE AMPLITUDE LOADING

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ABSTRACT

Fibre Metal Laminates *(ARALL, GLARE)* are characterized by several interesting properties. The fatigue crack growth resistance is outstanding thanks to fibre crack bridging. In the present paper results are presented of crack propagation under constant amplitude loading and flight-simulation load histories. Fibre-crack bridging and controlled delamination around fatigue cracks can be predicted by a model of Alderliesten for constant amplitude load cycles. This problem is now investigated under variable amplitude loading. Results will be presented. Limited interaction effects on the delamination are observed. Prospects for future applications in aircraft structures are indicated.

1 INTRODUCTION

Fibre Metal Laminates *(FMLs)* are fatigue efficient materials with exceptional damage tolerance properties. *FMLs* are built up of alternating thin metal sheets and unidirectional high strength fibres. In the past *FMLs* have been thoroughly investigated specially in the area of fatigue crack growth and related mechanisms [1]. Major part of these investigations [2] concern Constant Amplitude *(CA)* loading in order to understand the basic phenomena followed by limited work dealing with Variable Amplitude *(VA)* loading [3, 4] and flight spectrum loading [5, 6]. But still behaviour of *FMLs* under *VA* loading needs to be further investigated and developed.

At Delft University of Technology Delft, intensive research has been done in order to study the different fatigue related phenomena of *FMLs*. In 1988 a fatigue crack growth prediction model mainly for ARALL was developed [7] followed by another more accurate and generic model in 2005 [8]. The second

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model is capable of predicting fatigue crack growth, bridging stress distribution and delamination shape (profile) under *CA* loading. Now the question arises, whether and how Alderliesten *CA* model can be applied to *VA* loading cases.

In order to answer this question as well to understand the behaviour of *FMLs* under *VA* loading, it is necessary to investigate the effect of *VA* loading on the two main phenomena, delamination and fatigue crack growth. Since the delamination and crack growth are interrelated and hence, delamination and crack growth tests have been performed. Crack growth tests have been performed using Centre Crack Tension *(CCT)* specimens while the delamination tests have been performed using double crack lap share *(DCLS)* specimens. Different *VA* loading sequences like block loading, programmed block loading, etc. are used in the tests. Test results have been correlated with the prediction done by the simple *VA* loading crack growth model implemented in Alderliesten model.

This paper describes the experiments and results. The predictions models are compared to the data and the correlation is discussed.

2 FIBRE METAL LAMINATES

ARALL [7], *GLARE* [1] are two famous members of the *FMLs* family developed at Delft University of Technology. Unlike *ARALL, GLARE* has good fatigue properties in combination with compressive loading [9].

For standard *GLARE*, aluminium (alloy) 2024-T3 sheets and S2-glass fibres are bonded together with FM94 epoxy adhesive to form a laminate. This stack is cured in an autoclave at 120 °C and 6 bar for $1 - 1/2$ hour. The fibre orientation is defined with respect to the rolling direction of the aluminium layers and each orientation represents a prepreg layer of 0.133 mm thickness. Detailed description of *GLARE* grades are given in [1].

2.1 FATIGUE MECHANISMS

The metallic layers in *FMLs* show fatigue crack growth similar to monolithic metals and the composite layers show delamination at the metal-composite interfaces. The fibres in *FMLs* are insensitive to the fatigue loading, while the metal layers exhibit crack initiation and propagation. The fibres transfer load over the fatigue crack in the metal layers and restrain the crack opening. This phenomenon is called fibre bridging (Figure 1). Another phenomenon illustrated in Figure 1 is the delamination at the metal-fibre interface in the wake of the crack. The cyclic shear stresses at the interface as result of the load transfer from the metal to the fibre layers induce delamination growth.

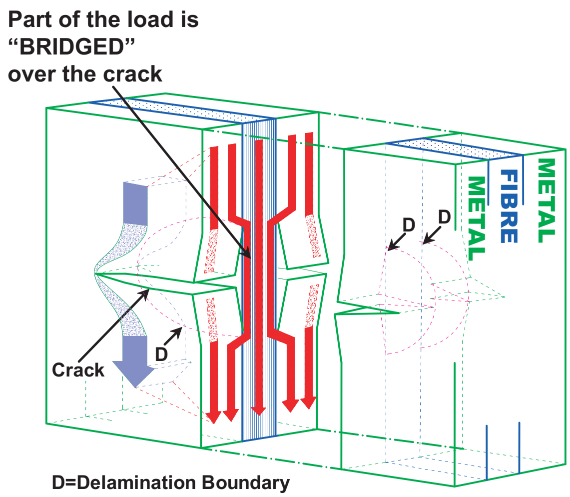


Figure 1: Crack bridging of the fibres and delamination of the layers [10]

Both the fatigue crack growth in the metal layers and the delamination growth at the interfaces form a balanced and so called coupled process.

3 EXPERIMENTAL PROGRAM

3.1 DELAMINATION

To study delamination, a *DCLS* specimen has been used. This specimen exhibits delamination growth independent of fatigue crack growth in metal layers, as shown in figure 2. Although this configuration has a mode I contribution to the delamination mechanisms [11], it was shown by Alderliesten et. al [12] that this mode has no effect on the observed delamination growth. The specimens have been manufactured with two 0.3 mm thick outer layers of aluminium 2024-T3 with sandwiched glass fibres epoxy layers. This configuration is based on standard *GLARE 2-2/1-0.3* [1].

3.1.1 TEST MATRIX

The experiments were conducted with block loading with a HI-LO, a LO-HI sequence, programmed block loading, multiple block loading and flight spectrum. The test matrix is given in table 1, showing the load sequence and the applied stress values.

3.1.2 TEST EQUIPMENT & PROCEDURE

The tests were conducted in lab air at room temperature on a closed loop mechanical and computer controlled servo-hydraulic testing system with a load capacity of 10 metric tons. The delamination lengths were measured from one side of specimen at the four locations near the artificial crack in the aluminium layers and then averaged. The delamination measurements were performed at

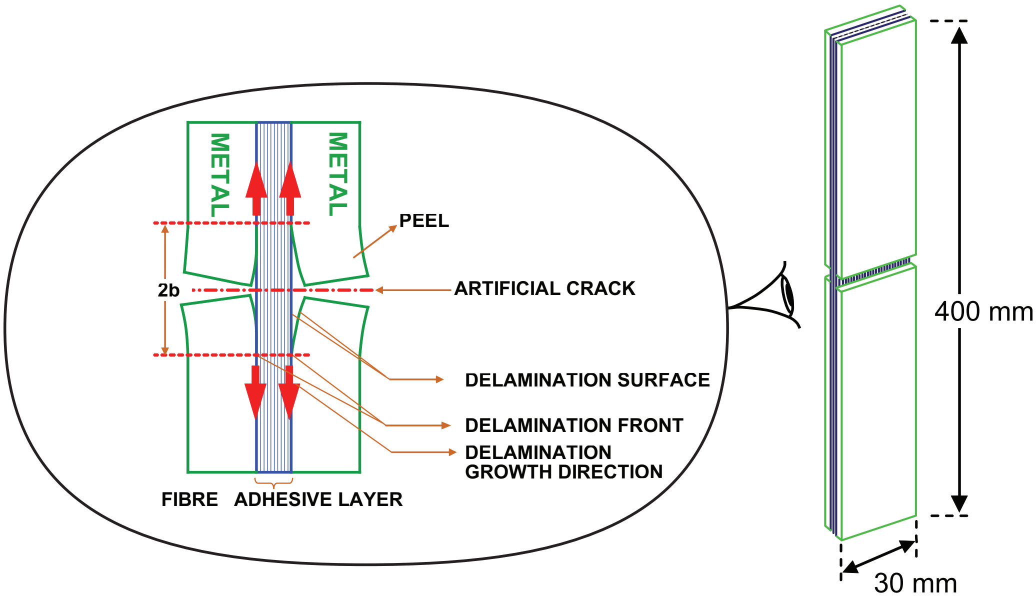


Figure 2: Double cracked lap shear specimen geometry

	Load Sequence	Stress Values [MPa]	Stress Ratio [R]
Block loading	LO-HI	150-169	0.05
	HI-LO	169-150	0.05
Multiple Block Loading	HI-LO	200-187.5-150-125	0.05
	LO-HI	125-150-187.5-200	0.05
Programmed Block Loading	I	105 to 195 in 285 cycles	0.86 to 0.03
	II	105 to 195 in 100 cycles	0.86 to 0.03
mini-TWIST		σ_{mean}=100	
SPECTRUM-I	Wide body fuselage spectrum		

Table 1: Delamination test matrix

intervals during the fatigue tests, while the test was on hold at its maximum applied stress level. The measurements were performed with a CCD camera using in-house developed imaging software Impress to capture the images and to enable measurements.

3.2 FATIGUE CRACK GROWTH

In the current model, fatigue crack growth predictions are done using either a linear damage accumulation or a yield zone model. Details about the application of these models to *FMLs* can be found in [10]. For the model validation, fatigue crack growth experiments on *GLARE 3-4/3-0.3* with cross-ply fibre orientation have been performed. These fatigue crack growth tests have been performed on center-cracked tension *(CCT)* specimens. The starter notches are made by drilling a hole of 3 mm diameter with two saw cuts, directing perpendicular to the loading direction. The total length of the starter notch ($2a_0$) is approximately 5 mm. The specimen geometry is discussed in detail in [10].

Load variation	CA cycles Maximum stress [MPa]	Stress ratio	Load variation [MPa]
Single overload	120	0.1	175
Multiple overload	120	0.1	175,158,139
Block loading-LO-HI	100	0.1	140
Block loading-HI-LO	140	0.1	100
Spectrum loading-I	Wide body fuselage spectrum		
Spectrum loading-II	Mega liner font fuselage spectrum		
Spectrum loading-III	Mega liner aft fuselage spectrum		

Table 2: Fatigue crack growth test matrix

3.2.1 TEST MATRIX

The experiments were performed on specimens made of Glare3-4/3-0.3. The CA cycles, between the load variations, had a maximum stress of 120 MPa and a stress ratio of 0.1. The test matrix is given in table 2.

3.2.2 TEST EQUIPMENT & PROCEDURE

The tests were conducted in lab air at room temperature on a closed loop mechanical and computer controlled servo-hydraulic testing system with a load capacity of 6 metric tons. The test frequency was 10 Hz.

4 RESULTS & DISCUSSION

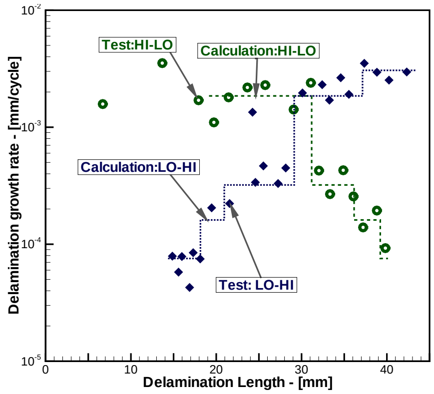
4.1 DELAMINATION

Block and multiple block loading cases' Results (Multiple block loading case shown in figure 3-a) have been presented before by the authors [13] with two main conclusions:

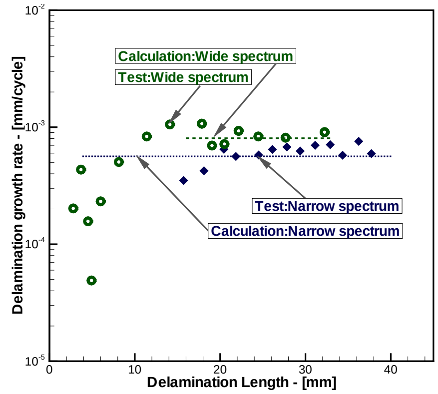
1. Delamination growth rate comes to a steady-state value for each load case and there exists an startup region with slow delamination growth rate. The size of the startup region is highly influenced by the maximum stress value. For example in case of LO-HI sequence this startup region is larger than the case of HI-LO sequence.

2. The delamination growth rate is related to the stress magnitude and is independent of the sequence. No matter if one starts with a low amplitude stress cycle and change to high amplitude or reverse the order of sequence, the delamination growth rate remains the same depending on the stress magnitude.

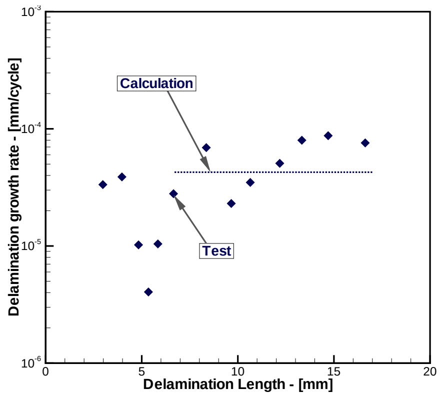
In order to study the effect of variable spectra and flight simulation loading spectra further tests have also been performed. For the better understanding of loading effect on delamination growth rate, linear damage accumulation calculations have been performed. Results of programmed block loading and flight spectra are shown in figures 3-b, 3-c, 3-e. Even in the case of these



3-a



3-b



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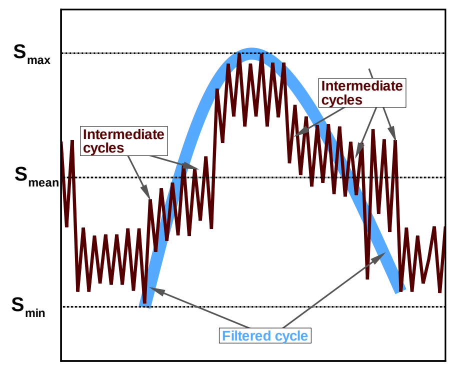
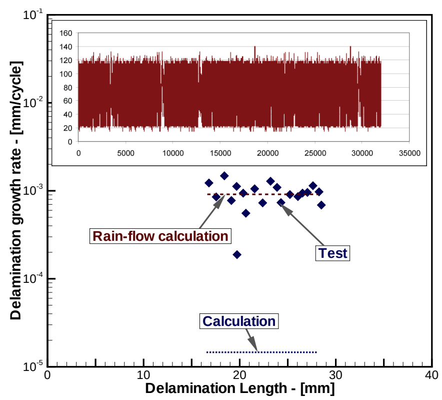
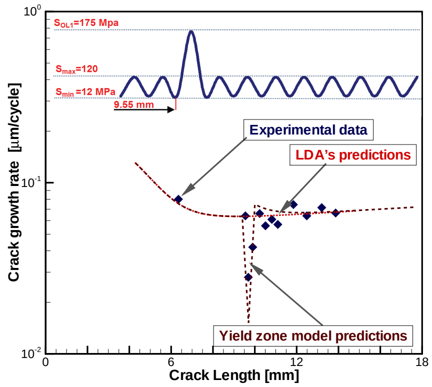


3-d

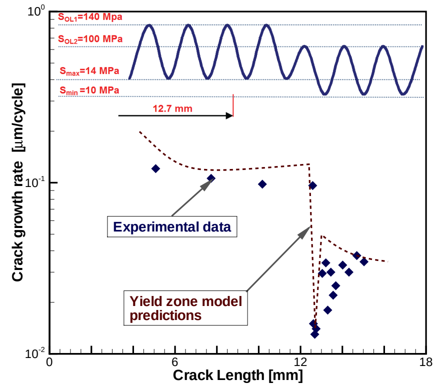


3-e

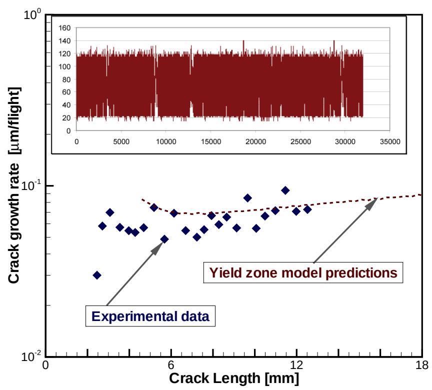
Figure 3: Delamination growth tests results: 3-a. Multiple block loading (Delamination rate Vs. Delamination length), 3-b. Programmed block loading (Delamination rate Vs. Delamination length), 3-c. Mini-TWIST (Delamination rate Vs. Delamination length - σ_{mean} =100 MPa), 3-d. Rain-flow counting procedure 3-e. Flight Spectrum I



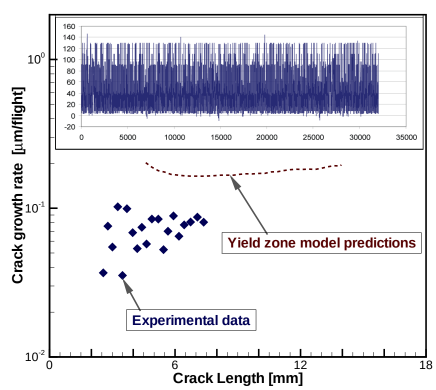
4-a



4-b



4-c



4-d

Figure 4: Fatigue crack growth tests results: 4-a. Single overload, 4-b. Block loading *(HI-LO)*, 4-c. Flight Spectrum-I, 4-d. Flight Spectrum-II,

spectra startup region exists and as the delamination starts to grow, steady-state delamination growth rate is attained. The linear damage accumulation *(LDA)* calculations are very close to the test data averages except the case shown in figure 3-e. The spectrum-I is having a number of intermediate cycles that break up the large cycles into smaller cycles. The rain-flow counting technique, mentioned in literature as a cycle counting and filtering technique, is used to omit these intermediate cycles. As a results, in the filtered situation the large cycles are considered, schematically shown in 3-d. As shown in figure 3-e, the rain-flow counting technique combined with *LDA* calculations resulted in a close match between the test and calculations. It also proves that the intermediate cycles in a large cycles do not contribute if the large cycles are considered as a single large cycle. Similar to rest of the test results, figure 3-e shows that the delamination growth rate attains a constant value as soon as it is out of the initial startup region.

Delamination growth under *VA* loading is independent of interaction effects, which make it possible to use the Alderliesten [8] *CA* delamination growth and shape prediction tool for prediction under *VA*loading.

4.2 FATIGUE CRACK GROWTH

The comparisons of predictions with the tests results are shown in figure 4. Figure 4-a shows the comparison for single overload of 175 MPa in the *CA* baseline cycles of $S_{max} = 120$ MPa and stress ratio $R = 0.1$. The *LDA* being a non-interaction model is unable to predict the retardation effect but on the other hand the yield zone model is able to predict the crack growth retardation in agreement with the experimental data. An interesting observation from figure 4-a is that there is hardly any difference between the yield zone model's prediction and experimental data after the application of overload. In other words, the number of delay cycles are almost equal which indicates that it is only the plastic zone that cause the retardation. In case of pure monolithic metals, predictions of yield zone model are quite far from the test [14]. However, for *FMLs*, the error is limited because of the intact fibres which restrain the crack opening leading to the small plastic zone formation which is comparable to the one calculated by yield zone model.

In single overload case (figure 4-a), the crack growth rate gets back to original level depending on the magnitude of S_{OL} and R_{OL}. It is known from the literature that in metals the retardation region is highly influenced by the magnitude of S_{OL}, and similar behavior is seen in case of *FMLs*.

Figure 4-b shows the comparison between test results and the yield zone model predictions in case of the High-Low block loading sequence. The retardation level is computed by the yield zone model. Similar to metals, in *FMLs* a large block of overload cycles creates larger plastic zones resulting in large retardation and related phenomena.

The comparison of the spectrum I is shown in figures 4-c. The comparison of test results with the yield zone model predictions for the spectrum I show very small error. But for the spectrum II (figure 4-d) the yield zone model predictions are quite far from the test results. The difference lies in the spectrum itself, because the number of overload cycles in spectrum II are more than in spectrum I. In the yield zone model's predictions and experimental results, it is obvious from the plot (4-a) that da/dN gets back to the original level as soon as the retardation effects are over. While in case of spectrum II it looks like the crack tip is trapped in frequently occurring overloads and plastic zones. We can also relate this behavior to de Koning's [15] primary and secondary plastic zone concept that makes the large difference between the prediction and test results.

5 CONCLUSION

Under *VA* loading, the exceptional fatigue properties are observed similar to *CA*. The overload and block loading experiments show signs of interaction effects (crack growth retardation). On the other hand, due to the presence of the fibres, the interaction effect can be considered as limited interaction effects in comparison to monolithic metals.

In order to understand the interaction effects a non interaction and simple interaction model has been used. The results from non-interaction model correlates well with most of the experimental tests consisting of simple *VA* and flight spectrum loading. Unlike monolithic metals there is a limited interaction effects in *FMLs* and a simple interaction model can be used to predict the fatigue crack growth. However, in case of a spectrum having frequently occurring overloads, this simple interaction model is insufficient.

Delamination tests under block, programmed block and flight spectra show no history or interaction effects. Even, the mismatch between the test data and *LDA* predictions shown in case of flight spectra, is overcome by applying the rain-flow counting technique to the spectrum. The correlation of test data and rain-flow counted spectrum results highlights that the delamination growth rate depends on the large cycles and the delamination is not effected by the intermediate cycles that breaks up the large cycles. Finally, the absence of interaction effects in delamination growth rate during *VA* loading proves that the Alderliesten's delamination calculation method can be applied in the case of *VA* loading with the rain-flow counting technique to consider the higher cycles only. However, it should be considered that for fatigue crack growth prediction the spectrum can be different from the filtered spectrum used for delamination.

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