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MODELLING OF FIBER METAL LAMINATE (FML) COMPOSITE USING THE RESIDUAL STIFFNESS AND STRENGTH MODEL

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ABSTRACT

The fatigue behavior of FML composite is so diverse and complex that present knowledge is far from complete. Two commonly used approaches to model fatigue damage are residual stiffness and the residual strength approach. In this paper, residual stiffness and the residual strength model is simulated. The model approach is in way: the damage growth rate-a measure for stiffness loss- is expressed by two separate terms representing the initiation and propagation phase of damage respectively. The model is capable of simulating the three stages of stiffness degradation: initial decline, gradual reduction, and final failure, as well as the stress redistribution due to the loss of stiffness in the damaged zones. The experiment also was carried out in this study.

Keywords: FML, Fatigue, Residual stiffness and the residual strength model, Composite

INTRODUCTION

Fiber Metal Laminates (FML) is a kind of hybrid materials and it can be fabricated from an alternating laminate of thin metal sheets and thin composite layers. Since several variables are involved in the composition of this laminate, a wide range of different combinations lamination seems to be possible. Some of these variables are the type of metal alloy, the type of fibers, the type of polymer, the thickness of layers, the number of layers, the orientation of (fibrous) layers, etc. Therefore, FMLs are regarded as a family of laminates, and GLARE is the best-known member of these laminates. GLARE is made from aluminum layers in the range of 0.3–0.5 mm thick, and glass fiber reinforced composite layers in the range of 0.25–0.5 mm thick (Volt and Vogelesang, 1999). One of the wide used of GLARE composite is in aeronautic application.

Based on the expected growth of passengers for intercontinental flights within the world, high capacity aircraft (such as from the Airbus company) are currently developed. To make this airplane cost effective for the next 30 years, new technologies are being evaluated such as the application of new aircraft materials. One of these studies investigates the feasibility of using the FML in the upper part of the aircraft that needs to be fatigue failure resistant, or specifically the structure should be under damage tolerant design (Sinke, 2003). GLARE composites have better resistance characteristics, such as high fatigue resistance, and also having an improved resistant in corrosion, particularly in the extreme temperature (Alderliesten, 2003).

As early as 1923, Palmgren (Theodore and Vassilopoulos, 2004) published hypothesis which is now generally known as the Miner rule or the linear cumulative damage hypothesis. According to Palmgren applying n times a cycle with a stress amplitude S and a corresponding fatigue life N is equivalent to consuming a portion of n/N of the fatigue life. Failure occurs when 100% of fatigue life is consumed. A failure thus occurs when:

$$\sum \frac{n}{N} = 1 \qquad (1)$$

However, Palmgren did not give any physical derivation for the rule. He was in need for an estimate of the fatigue life under Variable Amplitude (VA)-loading, and he adopted the simplest assumption for fatigue damage accumulation. Miner introduced the idea that the fatigue damage that fatigue damage is the consequence of work absorbed by the material which was assumed to be proportional to the number of cycles (Schijve, 2003).

The new model was formulated by Van Paepegam and Degrieck (2002) for which this model is capable to simulate three stages of stiffness degradation that can be found in FML materials, i.e. sharp initial decline; gradual deterioration; final failure. Since this model was already applied in fiber reinforced composites, thus, it is assumed that it can be also implemented for the FML composites.

The objective of this paper is to numerically simulate two commonly used approaches to model fatigue damage are residual stiffness and the residual strength .

LITERATURE BACKGROUND

Composite

Fiber Metal Laminate can be said to have a high fatigue resistance, with it is achieved by the intact bridging fibers in the wake of the crack. This condition restrains the occurrence of the crack opening (Vlot and gunnink, 2001). Controlled delaminating in the material makes some crack opening possible without failure of the fibers. The fibers transfer load over the fatigue crack in the metal layer and restrain the crack opening. This phenomenon is called fiber bridging (Alderliesten, 2007). The fatigue fibers laminates can be formed and machined like aluminum alloys and have the high specific strength of composite materials: they combine the best of both worlds. The laminates can be applied in various thicknesses, e.g. a 2/1 lay-up means a laminate with two aluminum layers and one intermediate fiber/epoxy layer: [A1/prepeg/A1]. The fiber/epoxy layer at 2/1 lay-up can be multiple cross plied 0/90 layer or be unidirectional (Shim and Alderliesten, 2003).

Fatigue Damage Formulation

The used of the phenomenological model for this study is based on the residual stiffness approach. Hence, the stress and strain are related by the commonly used equation in continuum damage mechanics. This stiffness degradation model, which is applicable for fatigue life assessment for a FML composite, was developed by Van Paepegam and Degrieck. It can be said as an improved model to date for the analysis of a FML specimen under a cyclic pattern of constant and variable stress/strain loadings. This model is mathematically defined as the following equation:

$$\overline{\sigma} = \frac{\sigma}{1-D} = E_0 \varepsilon \qquad (2)$$

Where $\overline{\sigma}$ is the effective stress, σ is the applied nominal stress, ε is nominal strain, E_0 is the undamaged Young's modulus. From Equation (2), the fatigue damage value can be calculated using Equation (3):

$$D = 1 - E / E_0 \qquad (3)$$

The damage (*D*) value is lying between zero (virgin material state) and one (final failure). The main drawback of the residual stiffness models is that they do not provide a means to estimate the moment of final failure. This problem is solved by establishing a relation between the damage variable *D* (measure for the residual stiffness) and a "fatigue failure index". The fatigue failure index is the ratio of applied effective stress $\overline{\sigma}$ to the static strength; it has value between zero and (applied stress equal zero) and one (effective stress equal static strength). This measure for the applied stress in relation to the static strength is now used in the damage growth rate equation dD/dN that is given by:

$$\frac{dD}{dN} = c_1.\Sigma \exp(-c_2.\frac{D}{\sqrt{\Sigma}}) + c_3.D.\Sigma^2.[1+\exp(c_5(\Sigma - c_4))] \qquad (4)$$

In the damage growth rate of the damage equations, all five constants c_i (i=1,…,5) have a distinctive meaning :

- c_1 Regulates the growth rate of the damage initiation regime (and thus the sharp initial decline of the modulus degradation curve),
- c_2 Is sufficiently large, so that the first term disappears when damage increases. Then, the steady state of matrix cracking, the so-called "characteristic Damage State" has been reached
- c_3 Represent the growth rate in the second stage of modulus degradation. Additional damage mechanism (fiber/matrix delaminating, pull-out from fibers out the matrix, initial fiber breakage) are developing gradually in the stage of fatigue life,
- c_4 and c_5 express the explosive damage growth once that the failure index $\Sigma(\sigma, D)$ approach its failure 1.0 and the effective stress $\overline{\sigma}$ approaches the static strength in tension or compression. When the threshold c_4 has been crossed, fiber fracture starts to propagate and finally causes failure in that material point.

METHODOLOGY

Experimental Works

In order to prepare the FML specimen, the open mold process was used, and this mold was fabricated using a steel type material. During the lamination process, the combination fabricating and curing procedure of aluminum plate and resin were accounted for. The gel coating procedure was then applied in order to obtain a good surface finish of the specimen.

The fabrication process of FML specimen used hand lay-up method, for which the fiber and epoxy were manually placed, and the excessive air was drawn using a vacuum bag. The hardening procedure was carried out within the room temperature. This process was accelerated with an additional heating and also mixed with an additional hardener.

The FML curing process was performed up to 120°C with the heating rate of 2.5°C/min. In order to avoid the trapped air in the prepreg, the vacuum bag was then used. This prepreg was covered by a vacuum bag and it was positioned in the autoclave for the curing procedure. The sample of specimen produced using the stated methodology is shown in Fig. 1.

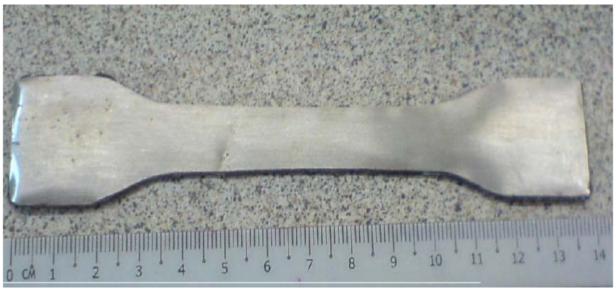

Figure 1: The geometry and shape of FML specimen used in this study

The other method that can be used for the specimen preparation is compress with the similar pressure and temperature (Botelho and Pandini, 2005). Due to the lack facility of this hot compress method, this alternative procedure cannot be performed.

The strength test has been carried out for several FML specimens. The tests were performed using the 25 ton capability of a servo-hydraulic power universal testing machine. Using the tensile test, the properties of the tensile strength and also tensile modulus of the specimens can be obtained, as tabulated in Table 1. Figure 2 shows a FML specimen fitted at the Fatigue machine before the test.

Figure 2: A FML specimen fitted at the fatigue machine

Experiment

From the S-N curve which was obtained from experiment we know that, the number of cycle increases when the strength decreases

Evaluation of damage acceleration factor

The model of Equation (1) was computationally simulated using the material properties listed in table 1.

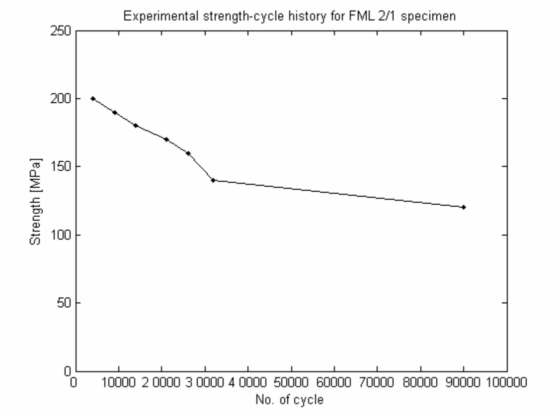

Fig. 3 S-N curve which was obtained from the experiment

Table 1 Material properties obtained in the experiment and the literature-based model parameters

Material properties		Model Parameters	
XT	260	c_1	0.002
Elasticity Modulus (GPa)	70.13	c_2	30.0
		c_3	4×10^{-6}
		c_4	0.85
		c_5	93.0

These values were obtained from the tensile test specimens. These values then will be used with literature based model parameters in order to obtain the damage acceleration factor of a specimen. From the simulation works using the parameters in Table 1 and the mathematical model of Equation (4), it shows that the damage growth of material significantly increases when the FML specimen was slightly failed or the value of damage equal to 1, and this damage growth trend is plotted in Figure 4 It shows that the damage growth is significantly creased when the damage value between 0.9 to 1. Figure 4 finally shows the damage acceleration factor forces to increase explosively.

Residual Strength

Since the degradation curve of the strength is very similar in shape with the stiffness degradation curve for most common materials (pepegem et al 2002). In the function *RS XT(1-D)^p*, *t*he power *p* is greater than 1.0, because this would imply that the strength degradation occurs faster than the stiffness degradation. When the power *p* would be smaller than 1.0, the behavior is not adequate as well, because the tensile stress is then degrading faster than the residual strength which leads to an failure index. Figure 5 illustrates this with a simple numerical example which shows the evolution of residual strength RS with damage, for a constant strain amplitude *p*=1.5, *E*0=700 GPa and *X*T=260.

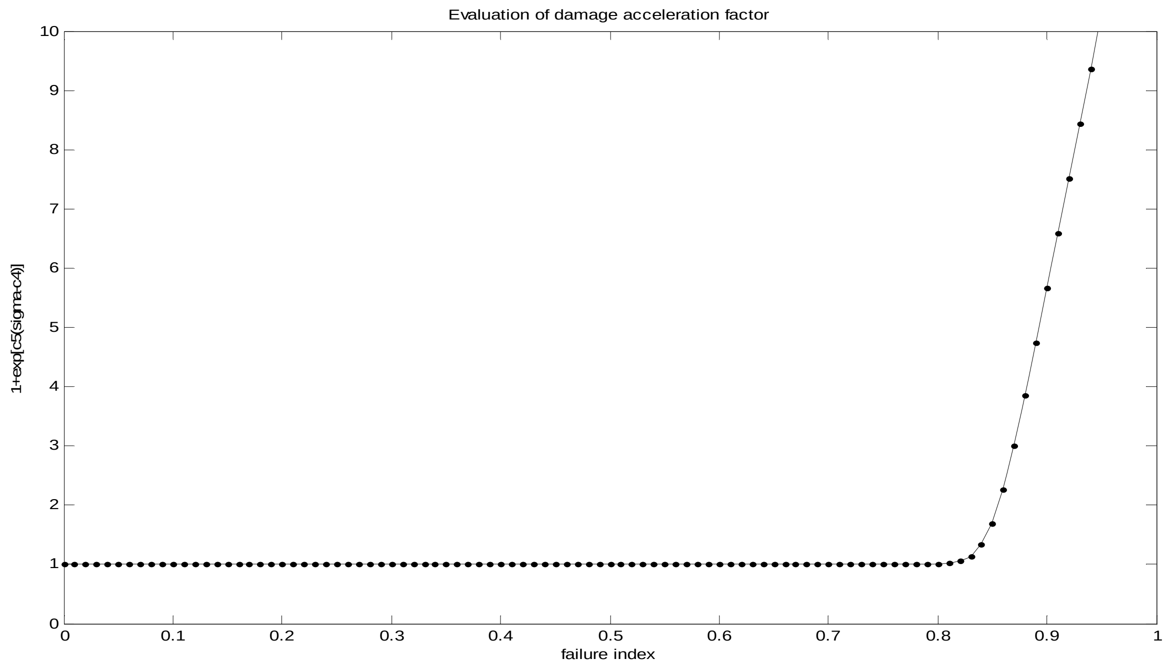

Fig. 4 S-N curve which was obtained from the experiment

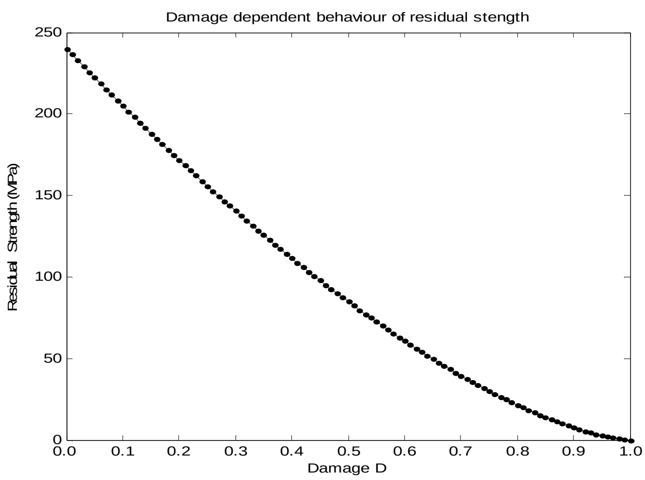

Figure 5: Damage dependent behavior of residual strength

MPa. As the failure index should remain a measure for the ratio to failure strength, even under fatigue, the failure index should increase when fatigue damage *D* increases. An inspection of the cause leads to the following conclusion: since the stress degrades linearly When this expression is considered, a different interpretation of the concept of "residual strength" is possible: Fatigue failure occurs when the effective stress equals the initial static strength XT, and the material static strength only decreases apparently during fatiguelife because the measured failure load with residual strength tests is divided by the initial cross-section Ao and not by the actual cross-section Ao(1-D). The load-bearing area is reduced (as compared to the static test) and the residual strength is smaller than the initial static strength (Paepegem and Degrieck, 2002).

CONCLUSION

The fatigue damage model had been used to simulate the effect of loading on fatigue test with FML composites. The simulation of FML damaging loading was due to residual stiffness and strength. The model was computationally modeled using the material properties and literature-based parameter. These values were obtained from the tensile test and also from literature.

Using both experiment and simulation data, it can suggested that the load and the mathematical model of Equation (4), it shows that the damage growth of material significantly increases when the FML specimen was slightly failed or the value of damage equal to 1, the damage growth is significantly creased when the damage value between 0.9 to 1.

Although the model is based on the residual stiffness approach, it can provide prediction about the residual strength as well.

In this case, a FML-specimen is said to be at failure condition when there is delamination effects between laminates and also the occurrence of small crack on the specimen surface. Finally, it is also concluded that the damage growth of material was significantly increased when the material damage value in between 0.9 to 1, according to the Palmgren-Miner's linear damage rule.

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