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THE EFFECT OF THE STANDARD DEVIATION AND THE AVERAGE LOAD OF A SPECTRUM LOADING ON THE LIFETIME OF COMPOSITE LAMINATES

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ABSTRACT

During service life, the composite structures are usually exhibited to several failure modes and their interactions that pushes both designers and researchers to characterize / identify the relevant parameter(s) for damage resistance, accumulation and life prediction.

In this paper, we aim to identify to what extent interlaminar stress causes relevant degradation of composite materials subjected to service loading spectra. Series of constant amplitude fatigue tests were carried out on [±45/0/90]3S graphite/epoxy laminate in order to determine S-N curve at load ratio r = Fmin/Fmax of 0.1. Further, based on these test data found, and to predict fatigue damage of specimens, linear model based on linear damage accumulation theory was employed. For three simulations of randomized loading spectra, predicted fatigue life generated were compared with quasi-empirical model and experimental results available on literature. Then, we move to study the effect of the standard deviation and the average of spectrum loading on specimen's lifetime.

Keywords: composite laminates, service lifetime, damage resistance.

INTRODUCTION

As known, today composite laminates are dominant in many civilian and military applications, such as aircraft, where we find that wings are manufactured of graphite/epoxy composite material that is the subject of our study. These structures are usually subjected to multi-axial fatigue loading due to external loads that are mostly random. Consequently, several types of defects such as fiber breakage, matrix cracks, and delamination occur which causes the degradation of global stiffness and residual strength of the laminate [1, 2].

Among many models that address this problem of damage, Yung-Li Lee and Tana Tjhung used Palmgreen-Miner rule, also known as the LDR (Linear Damage accumulation Rule) which is considered the simplest and most popular one, combined with the so-called rain flow cycle counting technics to assess damage or life of composite [3-4]. The rain flow cycle counting algorithm is found to be the best method for fatigue damage estimation [5-6] and is commonly applied as a reference to check the accuracy of frequency-domain methods [7-8]. The most successful predictive models generally take account both the rapid accumulation of damage in the first little cycles and rapid growth of damage at the end of fatigue life [9-10]. These models are extremely important because they allow the prediction of the onset and propagation of multiple off-axis cracks because these phenomena may be responsible for a pronounced reduction in stiffness well before the final failure of the laminate.

Due to lack or paucity of experimental data, not all approaches cited above have been validated experimentally and authors cannot verify their models or form any generalizations. Additionally, most of the studies have been made on composite materials subjected to tension (pull-out) and compression (push-in) static and/or dynamic tests but either no or very limited studies are available on the fatigue behavior under static / dynamic bending tests. Consequently, some authors have taken a different path from the deterministic one, they based on the finite element analysis and calculation of damage using various computer code, such as ABAQUS [11], LS-DYNA [12], FADAS [13-14].

Hence, in this paper we have chosen specimens with geometrical parameters leading only to delamination failure mode knowing that the thickness of the samples was fixed in advance by the manufacturer of the aircraft wings F16 (h=3.47 mm). In the second place, spectrum fatigue damage was predicted using model, which was derived from empirical laws (Miner's rule) and fatigue tests data. Comparison of obtained results with mathematical formula E(D) and experimental test results available on literature demonstrate that the predictive capabilities of the proposed model are quite satisfactory. Then, we examined the effect of standard deviation and the average of loading spectra on fatigue life of samples. CMEEE.congress@gmail.com

EXPRIMENTAL STUDY

The tests were performed via MTS 810 servo hydraulic machine, the material used for the experimental study was Hercules AS4/3501-6 quasi-isotropic graphite/epoxy composite laminate [±45/0/90]3S, the specimens are loaded in three point bending (Fig. 1) with linear constant.

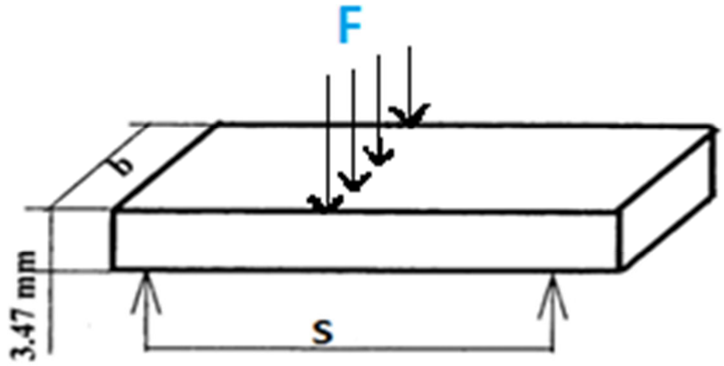

Fig. 1 - Geometric dimensions of the specimen

There exist many fracture modes that could be encountered in the laminate; for this reason, the dimensions of specimen have been previously set so that only interlaminar fracture at the central 90/90 interface will be generated as the dominant fracture mode.

Our interest of delamination failure mode comes from the fact that this type of damage occurs abruptly within layers (invisible), also it is considered as the most dangerous and severe defect because it may severely degrade the stiffness and strength of composite structures JM. Hodgkinson [**7**] and SR. Reid and G. Zho [**8**]. Following an experimental study, we concluded that dimensions of the specimen leading only to interlaminar delamination fracture mode are b=10 mm and S=30 mm.

Thereafter, thirty specimens were tested under different load levels at a load ratio $r = \frac{F_{min}}{F_{max}} = 0.1$. The test results are given in the form of an S-N curve in Fig. 2 and from a straight line corresponding to the best fit of the data in the log-log scale, we extract constants β = -0.1077 and c =3.69 characterizing the equation of the straight line given by:

$$\text{Log F} = \beta \log \text{N} + \text{c}. \tag{1}$$

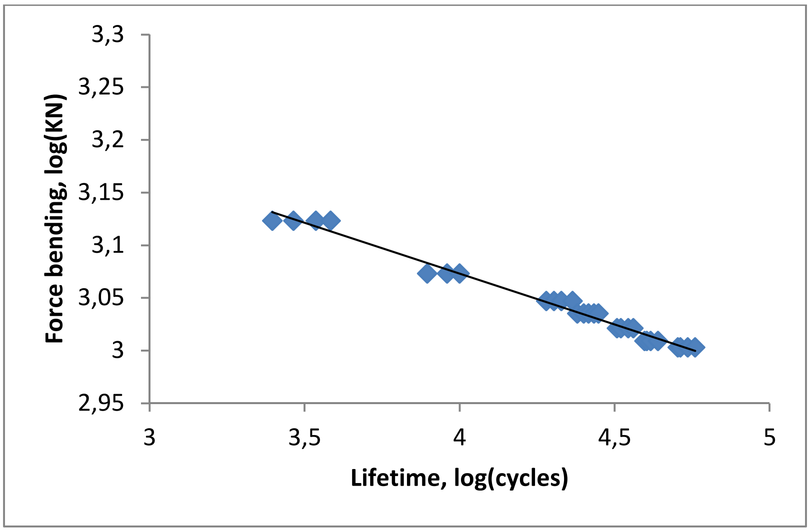

Fig. 2 - Curve of constant load amplitude fatigue in a log-log diagram

FATIGUE LIFE PREDICTION MODELS:

In what follow, our study is based on a stationary ergodic Gaussian loading.

linear damage model:

Using a Matlab program, we generate an ergodic Gaussian stationary random signal (Fig. 3); then we counted cycles using rainflow cycle counting algorithm according to the ASTM standard. In addition to number of cycles, the program returns rainflow amplitudes and means values of the load that will serve us to calculate the load Fa that will be used to extract lifetime Ni from S-N curve already drawn before (Fig. 2). Based on Haigh diagram, load F was calculated as follows:

$$Fa = \frac{\text{Frupt}*\text{Farainflow}}{\text{Frupt} + (\text{Farainflow} - \text{Fmrainflow})} \;. \tag{2}$$

Where Frupt being the ultimate load, Farainflow and Fmrainflow represents rainflow amplitudes and means values returned by the algorithm. In order to calculate lifetime we used a following expression:

$$T = \frac{\sum(Farainflow)i}{\sum\frac{ni}{Ni}}. \tag{3}$$

Where n_i represents rainflow cycles obtained from the counting procedure of the algorithm (Figure 4).

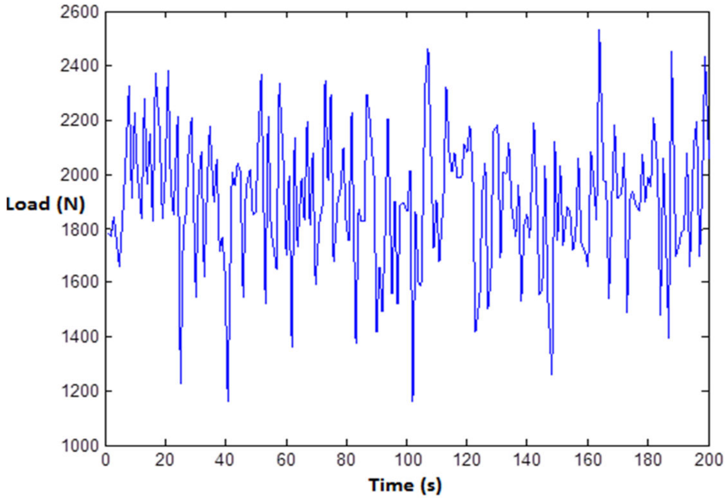

Fig. 3 – Ergodic Gaussian stationary random loading generated

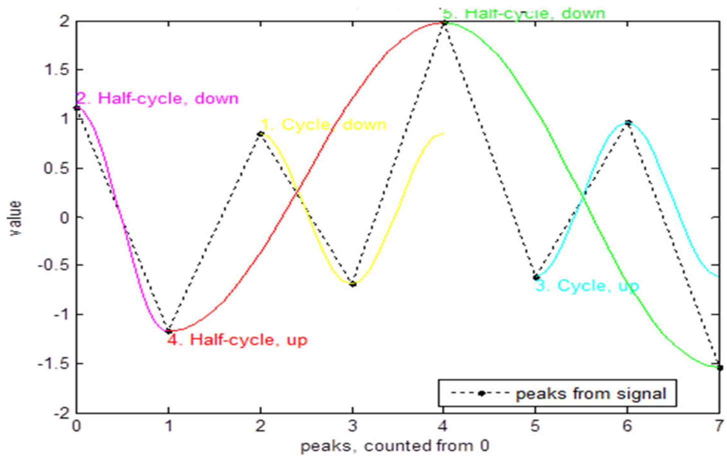

Fig. 4 – Rainflow cycles extracted from signal

Quasi-empirical model:

According to linear damage rule, the expected damage can be calculated as [**3**]:

$$E[D(t)] = C^{-1}\nu_p \int_0^{+\infty} S^{\beta} p(S)\,dS \tag{4}$$

Where, ν_p is the frequency of peaks, p(S) is the probability density of the maxima while C and β are material parameters defining the constant amplitude SN curve:

$$NS^{\beta} = C \tag{5}$$

For a Gaussian stationary process, the frequency of peaks is given by [**15**]:

$$\nu_p = \frac{1}{2\pi}\sqrt{\frac{m_4}{m_2}} \tag{6}$$

Where, m_2 and m_4 are the second and fourth spectral moment. The spectral moment is defined by:

$$m_k = \int_{-\infty}^{+\infty} |w|^k \,\phi(w)\,dw = \int_0^{+\infty} w^k \,\phi(w)\,dw \tag{7}$$

Where, ϕ(w) represents the power spectral density. The determination of the probability density of the maxima has been well studied [**16**]. As an example, in a narrow-band Gaussian process p(S) is a Rayleigh distribution so that equation (1) becomes as follow:

$$E[D(t)]=C^{-1}\frac{2^{\beta/2}}{2\pi}\sqrt{\frac{m_4}{m_2}}\sigma^{\beta}\,\Gamma(1+\frac{\beta}{2}) \tag{8}$$

Where, Γ (.) represents the gamma function defined by:

$$\Gamma(x)=2\int_0^{+\infty} t^{(2x-1)}e^{-t^2}dt \tag{9}$$

For an ergodic process, it is assumed that expectancy of the total damage over a period T of application of random loading is:

$$E[TD(t)] = TE[D(t)] \tag{10}$$

And we know that the ruin occurs when the total damage is unity, then estimation of the lifetime of composite can be deducted from equations (8) and (10):

$$T=\frac{1}{E[D(t)]}=\frac{1}{C^{-1}\frac{2^{\beta/2}}{2\pi}\sqrt{\frac{m_4}{m_2}}\sigma^{\beta}\,\Gamma(1+\frac{\beta}{2})} \tag{11}$$

For three different spectra simulated loads, we have compared results obtained through linear damage model with results found through mathematical expression (Eq. 11) and experimental results available in literature [2], results are summarized in Table 1.

Table 1 - Comparison of lifetime results

Loads	Linear model results	Theoretical results	Average lifetime with programmed blocks	Average lifetime with randomized blocks	Average lifetime with individual cycles
Case1: F=2000 (N); $\sigma = 350\ (N)$	5800 cycles	4900 cycles	3387.5 cycles	3912.5 cycles	4410 cycles
Case2: F=1500 (N); $\sigma = 500\ (N)$	63000 cyles	58000 cycles	52595 cycles	52905 cycles	54517.5 cycles
Case3: F=750 (N); $\sigma = 500\ (N)$	2.210^8 cycles	10^7 cycles	none	none	none

The linear model has experienced widespread use in metal fatigue application and has carried forward to composite fatigue. Designers know that results found by this model are non-conservative and are viewed with great suspicion, despite all this, it still used as a benchmark with which other models are compared. However, and despite defects present in the experimental process, we can still conclude that the quasi-empirical fatigue damage model, based on minure's rule, for variable amplitude loading is rather quantitatively accurate for engineering application.

EFFECT OF STANDARD DEVIATION AND THE AVERAGE LOAD OF SPECTRUM LOADING:

In this section, the effect of both the standard deviation and the average of the spectrum loading on the fatigue life was examined for a variety of service fatigue loading. For this purpose, firstly we have calculated lifetime by varying values of sigma from 100 to 500 and for 3 average amplitudes of the applied spectrum, and secondly we have varying the average amplitudes for various magnitudes of standard deviation of the service spectra. Results obtained are drawing in semi-log graphic as shown in fig. 5 and fig. 6.

It is clear from these figures, that for three different mean load, all curves obtained are parallel and decreases similarly, henceforth, equations governing these curves, of the standard deviation and the average amplitude respectivelly, has the following forms:

$$\text{Log N} = B\sigma^{-7.5} \tag{12}$$

$$\text{Log N} = KF_m^{-4.161} \tag{13}$$

Where, σ & F_m denotes respectively the standard deviation and the average amplitude of service loading. B is a parameter related to the average force of loading spectrum with the following empirical relationship: $B = 10^{38}Fm^{-4.16}$. K is another parameter related to the standard deviation of loading spectrum with the following expression: $K = 7E37\sigma^{-7.43}$. Both, Eq. 12 and Eq. 13 provides easily the lifetime of a composite laminate by knowing just the mean value and standard deviation of the applied load spectrum. It is worth noting that fatigue life decrease considerably when standard deviation (fig. 5) and average load (fig. 6) increase which is correlated with fatigue life behavior of composite laminates. We notice also that curves representing standard deviation vs lifetimes decreases rapidly than those representing the average load vs lifetimes, then, we conclude that the standard deviation have more influence on fatigue life of specimens than the average amplitude of service loads.

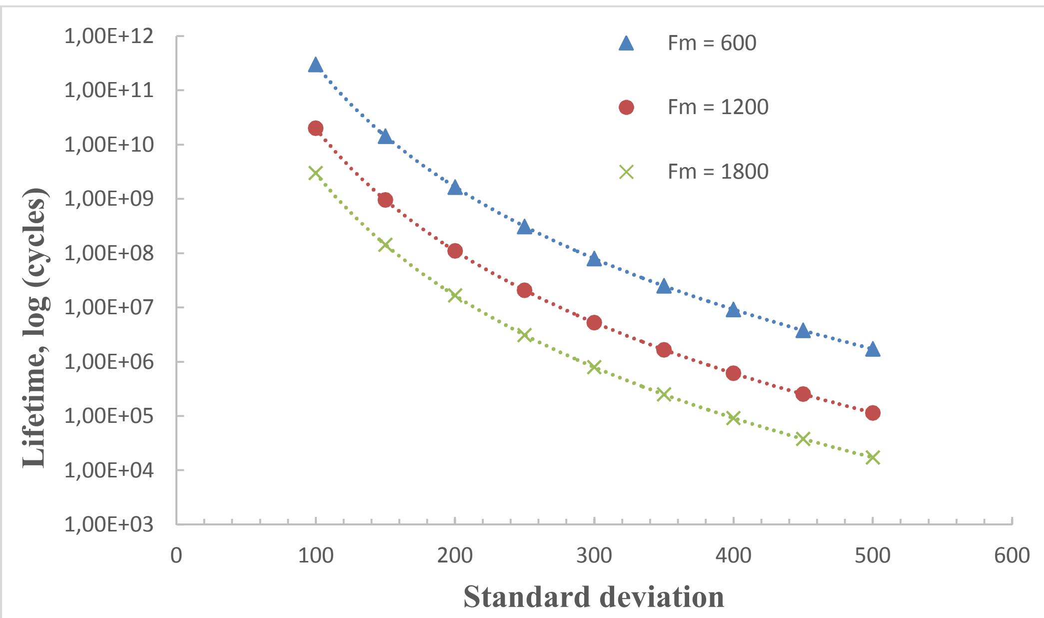

Fig. 5 - The effect of standard deviation on specimen’s lifetime

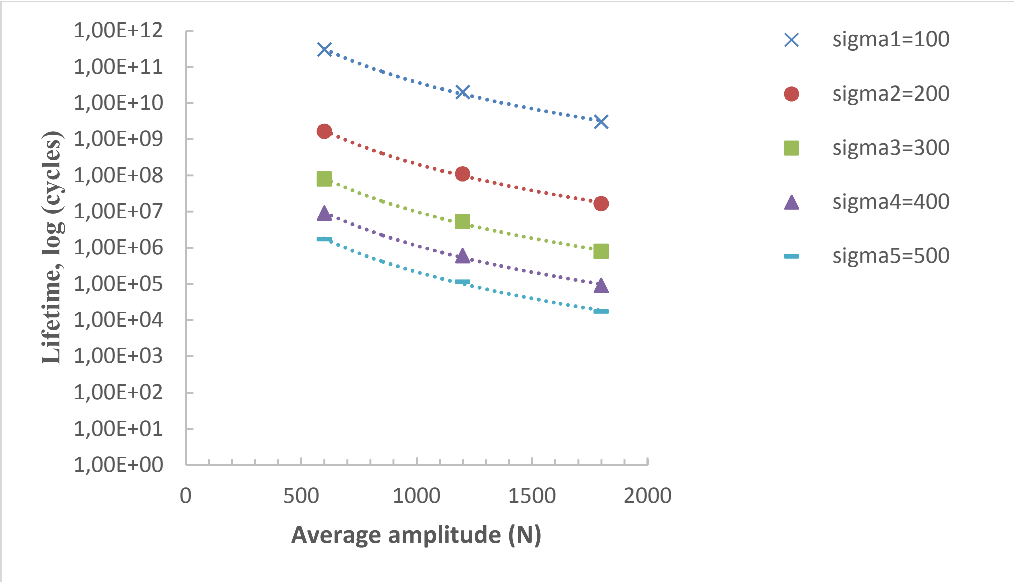

Fig. 6 - The effect of average load on specimen's lifetime

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