INEEL/CON-04-02017
PREPRINT

Fatigue Damage Evaluation in CFRP Woven Fabric Composites through Dynamic Modulus Measurements

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July 25 –29, 2004

ASME PVP 2004 International Conference

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1. INTRODUCTION

Advanced fiber reinforced composite materials offer substantial advantages over metallic materials for the structural applications subjected to fatigue loading. With the increasing use of these composites, it is required to understand their mechanical response to cyclic loading [(1)-(4)]. Our major concern in this work is to macroscopically evaluate the damage development in composites during fatigue loading. For this purpose, we examine what effect the fatigue damage may have on the material properties and how they can be related mathematically to each other. In general, as the damage initiates in composite materials and grows during cyclic loading, material properties such as modulus, residual strength and strain would vary and, in many cases, they may be significantly reduced because of the progressive accumulation of cracks. Therefore, the damage can be characterized by the change in material properties, which is expected to be available for non-destructive evaluation of the fatigue damage development in composites. Here, the tension-tension fatigue tests are firstly conducted on the plain woven fabric carbon fiber composites for different loading levels. In the fatigue tests, the dynamic elastic moduli are measured on real-time, which will decrease with an increasing number of cycles due to the degradation of stiffness. Then, the damage function presenting the damage development during fatigue loading is determined from the dynamic elastic moduli thus obtained, from which the damage function is formulated in terms of a number of cycles and an applied loading level. Finally, the damage function is shown to be applied for predicting the remaining lifetime of the CFRP composites subjected to two-stress level fatigue loading.

2. FATIGUE TEST

2.1 Test Specimen

Test specimens are layed up using 4 plain woven fabric carbon fiber prepregs-sheets of Mitsubishi Rayon TR000-3110 and fabricated by the autoclave molding technique. They are of strip type and 200 mm long, 10 mm wide, and 1mm thick, where the gage length is 100 mm, and also GFRP tabs are attached to both surface ends.

2.2 Dynamic Elastic Modulus Measuring System

A dynamic elastic modulus measuring system, as shown in Figure 1, is developed by incorporating a personal computer and an AE apparatus into a fatigue testing machine. The signals of applied load and elongation are transmitted into the personal computer for data acquisition and reduction.

2.3 Loading Conditions

Tension-tension fatigue tests are conducted using Shimazu survopulser EHF-EB10-20L machine, where cyclic loads with sinusoidal stress history are applied at a frequency of 5 Hz. The minimum stress σ_{min} is fixed to 85 MPa and the maximum stress σ_{max} vary between 75% and 90% of static tensile strength (σ_B= 580 MPa). Accordingly, the stress levels $S = \sigma_{max} / \sigma_B$ range from 0.75 to 0.90 and so the stress ratios $R= \sigma_{min} / \sigma_{max}$ vary from 0.19 to 0.16.

3. DAMAGE FUNCTION

Among various material properties varying with an increasing amount of damage, the stiffness of materials is employed for determining a damage function that corresponds to the damage development during fatigue loading, because it has advantages over other properties in that the stiffness, i.e., the dynamic elastic modulus may be measured nondestructively in service. Therefore, by using a dynamic elastic modulus $E(n,S)$ at a given number of cycles n at a stress level S, we define the damage function $D(n,S)$ by

$$D = \frac{E(0,S) - E(n,S)}{E(0,S) - E(N,S)} \tag{1}$$

where N is a number of cycles to failure.

So, if the dynamic elastic moduli, which are the gradients at a number of cycles on the stress-strain diagram during cyclic loading, are continuously measured on real time during fatigue loading with different stress levels or stress ratios, then they are formulated as a function of n and S or R, from which, using Eq.(1), the damage function is mathematically expressed with these two variables. It should be noted here that, in general, this damage function is dependent of a stress level or a stress ratio as well as a number of cycles.

4. RESULTS AND DISCUSSIONS

4.1 Dynamic Elastic Modulus

The dynamic elastic modulus was determined at four stress levels. Figure 2 shows the normalized dynamic elastic modulus $E(n)/E(0)$ as a function of a number of cycles n for the stress level $S = 0.80$ ($R = 0.18$). The variation of the dynamic elastic modulus, i.e., the stiffness degradation during cyclic loading has three stages, that is, an initial quick decrease, followed by a more gradual decrease, where the decreasing rate is almost constant, and a final rapid drop. The dynamic elastic modulus vs. the number of cycles makes no remarkable difference between stress levels and the stress level dependency was not found clearly. Therefore, the dynamic elastic modulus is a function of one variable alone and it forms the same curve given by

$$E(n/N) = -13.1\,(n/N)^3 + 21.8\,(n/N)^2 - 14.5\,(n/N) + 56.4 \quad (2)$$

4.2 Damage Function

By substituting Eq.(2) into Eq.(1), we have the damage function in the form of

$$D(n/N) = 2.3\,(n/N)^3 - 3.9\,(n/N)^2 + 2.6\,(n/N) \quad (3)$$

The damage function is graphically presented as a function of cycle ratio n/N in Figure 3. The damage grows quickly at the initial stage and then the increasing rate reduces and it remains almost constant, and lastly, it increases rapidly again.

4.3 Lifetime Prediction

Together with the cumulative fatigue damage rule proposed in the previous paper (5), the damage function is shown here to be available for predicting the remaining lifetime of CFRP composite materials. In order to verify the prediction, the two stress level fatigue tests are performed at two different combination of stresses. One is a stress increasing test (Low→High), where a lower stress is first applied and then a higher stress is done. The other is a stress decreasing test (High→Low), where the loading sequence is reversed. In these tests, n_1 cycles are operated at the first stress σ_1, and then the remaining number of cycles n_2 operated until the failure occurs at the second stress σ_2 is measured. The applied stresses are σ_1 = 493 MPa and σ_2 = 522 MPa for a stress increasing test, while σ_1 = 522 MPa and σ_2 = 493 MPa for a stress decreasing test. In both tests, a number of cycles n_1 operated at the first stage is 0.5 N_1, where N_1 is a number of cycles to failure at the stress σ_1. Table 1 shows the results. The predicted lifetimes are shorter than those obtained from the stress increasing and decreasing tests, and the difference between them is remarkable for the stress decreasing test.

5. CONCLUSION

Damage development during tension–tension fatigue loading is non-destructively evaluated in terms of a damage function formulated using a dynamic elastic modulus which continuously varies with an increasing fatigue damage caused by the progressive accumulation of cracks in CFRP woven fabric composites. The dynamic elastic modulus is a function of a number of cycles alone because of the stress independency, and it forms the same cubic curve for different stress levels or stress ratios, which decreases monotonously. On the other hand, the damage function is a monotonously increasing cubic one, from which the damage development in composites during cyclic loading is presented as a function of a number of cycles. The damage function is also applied for the remaining lifetime of CFRP composites subjected to two-stress level fatigue loadings and the prediction is experimentally verified.

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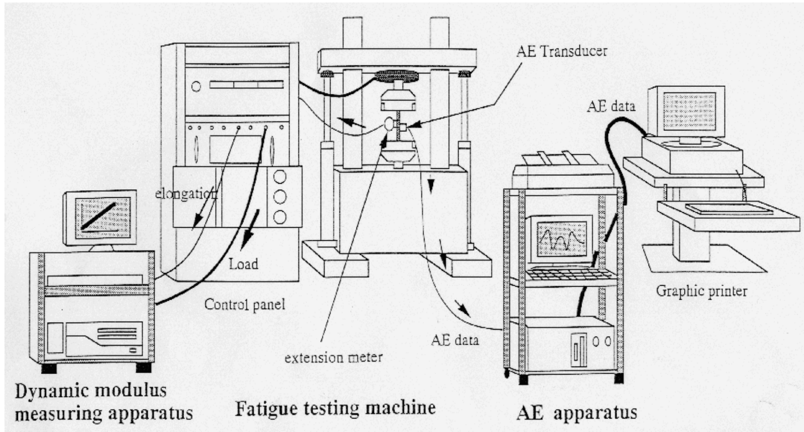

Fig.1: Dynamic Elastic Modulus Measuring System

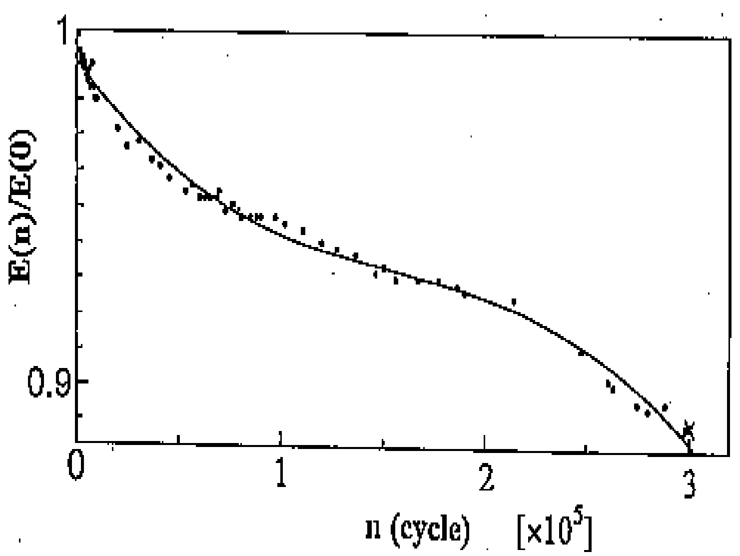

Fig.2 Dynamic Elastic Modulus vs. Number of Cycles

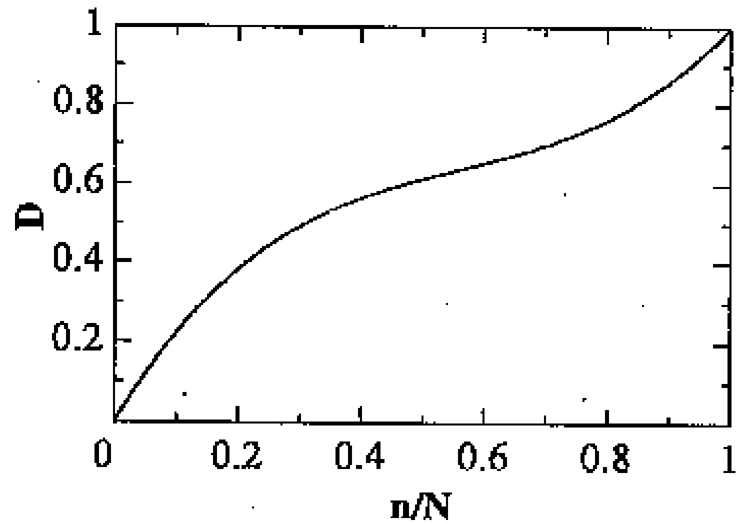

Fig.3 Damage Function vs. Cycle Ratio

Table 1 Comparison of Lifetime between Predictions and Experiments

No.	σ_1 (MPa)	σ_2 (MPa)	Experimental n_2 (cycle)	Theoretical n_2 (cycle)
		Low-High		
1	493	522	32500	21100
2	493	522	14100	21100
3	493	522	47200	21100
		High-Low		
4	522	493	22100	49000
5	522	493	177800	49000
6	522	493	203200	49000