ACCELERATED FATIGUE PROPERTIES OF SINGLE-FIBER COMPOSITES

S. S. Chen[1] & Shun-Fa Hwang[2]

[1]Department of Materials Science and Engineering, N H U S T, Huwei 632, Taiwan.

[2]Department of Mechanical Engineering, National Yunlin University of Science & Technology, Touliu 640, Taiwan.

ABSTRACT

Polymer resins exhibit viscoelastic behavior not only above the glass transition temperature but also below this temperature. It has been confirmed that composite materials using polymer resins as matrices have this viscoelastic behavior. Hence, one could accelerate the fatigue testing if the stress amplitude, frequency or temperature is changed. The purpose of this study is to invest the accelerated fatigue properties of single-fiber composites and to predict their life. For this purpose, this paper develops the all-life range of the sigmoid S-N curve that is under the assumption that the damage of a composite is a process of multiple initiations, coalescence of micro-cracks, and final failure. In order to establish the accelerated fatigue properties of glass/epoxy and carbon/epoxy composites, the fatigue testing of unidirectional specimens from different angel is conducted at room temperature under different stresses, frequencies, and stress ratios. The "time-frequency" and "time- stress" superposition are used to relate the fatigue behavior of the composites with time. Both the straight and sigmoid S-N curves are also proposed to show the effects of different stresses, stress frequencies, and stress ratios on the fatigue life. Comparing the straight S-N curves, the sigmoid S-N curves are recommended to express the accelerated fatigue data.

1 INTRODUCTION

Because of the complex failure modes of composites, their fatigue failure properties are complicated and hard to be predicted. There are many models proposed to analysis fatigue properties of composites. For example, Reifsnider [1] divided the processes of composite fatigue into three steps, the initiation of matrix cracks, the matrix cracking and delamination growth, and the fiber breaking as well as the failure of the whole composite. Besides, fatigue endurance limit, fatigue damage cumulative theory, stiffness degradation model and residual strength model, etc.

have been developed. In general, the popular style to present the fatigue data is S-N curve [2-5]. Furthermore, since polymer resins exhibit viscoelastic behavior not only above the glass transition temperature but also below this temperature, it has been confirmed that composite materials using polymer resins as matrices also have this viscoelastic behavior. Hence, the "time-frequency" and "time-stress" superposition are used to relate the fatigue behavior of the FRP with time. Miyano et al. [4-6] developed the master curve under different temperature. Rotem and Nelson [7] utilized temperature transformation factor to predict the fatigue life of the FRP. Some studies [7-10] investigate the influence of stress ratio and stress frequency on the fatigue behavior of composites. The purpose of this study is to invest the accelerated fatigue properties of single-fiber composites and to predict their life. For this purpose, this paper develops the all-life range of the sigmoid S-N curve that is under the assumption that the damage of a composite is a process of multiple initiations, coalescence of micro-cracks, and final failure. In order to establish the accelerated fatigue properties of glass/epoxy and carbon/epoxy composites, the fatigue testing of unidirectional specimens from different angel is conducted at room temperature under different stresses, frequencies, and stress ratios. The "time-frequency" and "time- stress" superposition are used to relate the fatigue behavior of the composites with time. Both the straight and sigmoid S-N curves are also proposed to show the effects of different stresses, stress frequencies, and stress ratios on the fatigue life.

2 THE EXPRESSION OF FATIGUE DATA

2.1 Straight S-N curve

Straight and sigmoid forms of S-N curve are utilized to present fatigue data. The form of straight S-N curve is shown as below:

$$\frac{S_a}{\sigma_u} = a - b \log N \tag{1}$$

where *a* and *b* are material parameters. Because the stress ratio (*R*) and stress frequency (*f*) could change the fatigue life, the position of the straight S-N curve will be changed. For each S-N curve, the values of *a* and *b* are different because of different *R* or *f*. According to the "time-frequency" and "time-stress" superposition theory, the *a* and *b* could be expressed as functions of stress ratio or stress frequency. The functions of *a(f,R)* and *b(f,R)* are decided by different straight S-N curves that are regressively plotted from fatigue testing data. Therefore, a master curve could be obtained by using these *a(f,R)*s and *b(f,R)*s to transform all S-N curves to a reference line.

2.2 Sigmoid S-N curve in all-life range

Assume that the fatigue of a composite is a process of multiple initiations, coalescence of micro-cracks, and final failure. Let *D(n)* be an index of the fatigue damage of the composite. Suppose the growth rate of *D(n)* is proportion to the quantity of itself, *D(n)*. Furthermore, the size of the specimen will limit to the growth rate of *D(n)*. One can derive the form of the growth rate of *D(n)* as below:

$$\frac{dD(n)}{dn} = D(n)\left(a - bD(n)\right) \tag{2}$$

where $n = log(2N)$. To solve this differential equation, one can presume that the s_a / σ_u is linear depend on *1-D(n)*. After applying the initial and ultimate conditions in the equation, one can obtain the following equation:

$$\frac{s_a}{\sigma_u} = \frac{k}{1+(k-1)(2N)^m} = \frac{(c+1)(2N)^{-m}}{c+(2N)^{-m}} \tag{3}$$

There are two parameters, *k* (or *c*) and *m*, which need to be decided by experiments. The profile of this equation is a sigmoid S-N curve and it could fit the full-range life of fatigue data. Again, the "time-frequency" and "time-stress" superposition theory could be applied, and experimental data in different *R* and *f* conditions could be utilized to obtain the functions of *k(R,f)* and *m(R,f)* for composite materials.

3 EXPERIMENTAL DETAILS

The fatigue tests of unidirectional specimens with different angels for two types of composites, which are glass/epoxy and carbon/epoxy composites, are conducted at room temperature under different stresses, frequencies, and stress ratios. The angles of the composite specimens are 0° and 90°. The stress levels of the fatigue testing are *60* ％ to *90* ％ of the strength of the composite. The stress frequencies are *1*Hz to *30*Hz. The stress ratios are *0* to *0.5*. When the testing were executed, the data of the stress, strain, stiffness, and hysteresis loops, etc, which were corresponding to the loading cycles, must be recorded.

4 RESULTS

The 0° and 90° composite laminate specimens are tested in the conditions of different *R* and *f*.

Figure 1 shows some tested data and the fitting straight S-N curves in the life periods of 10^3~10^6 cycles. It shows that different stress ratios cause different S-N curves, which have different slopes (b) and intercepts (a). Figure 2 and Figure 3 are the graphs of a and b versus R at $f = 1$, respectively. The fitting-curves in these figures indicate the relations between a or b with R, which can be expressed as $a(R)$ and $b(R)$. The different S-N curves in the Figure 1 can be transformed to a master curve by the relations of $a(R)$ and $b(R)$. The result is showed in Figure 4. To use the interpolation method to predict the $a(R)$ and $b(R)$ at an assigned stress ratio (R), one can transform the master curve to establish the corresponding S-N curve, which can predict the fatigue life of the composite specimens at the condition of this assigned stress ratio (R). The same process can be utilized to build the material parameters a and b corresponding to stress frequency f.

Figure 5 shows the full-range life of sigmoid S-N curves, which are obtained from different fatigue stress frequencies at $R = 0$ for 0° composite laminate specimens. It shows that different stress frequencies could result in different S-N curves, which have different material parameters k and m. By the fitting curves in Figure 5, the parameters k and m can be expressed in terms of f. Figure 6 and Figure 7 shows the distribution of m and k versus f at $R = 1$, respectively. From Figure 6 and Figure 7, one can use the interpolation method to predict the m and k at any fatigue stress frequency. Hence, a new S-N curve can be established without any experiments. The same process can be utilized to build the material parameters m and k corresponding to stress frequency R.

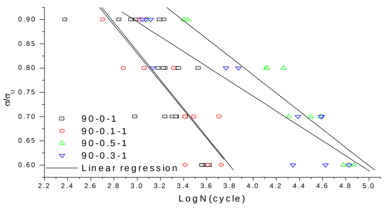

Figure 1: Straight S-N curves of 90^0 G/E laminate with different R ($R = 0, 0.1, 0.3, 0.5$) and $f = 1$.

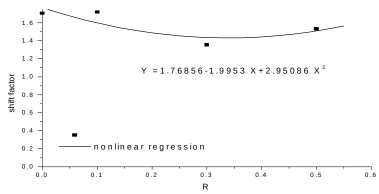

Figure 2: The function of a versus R at $f = 1$.

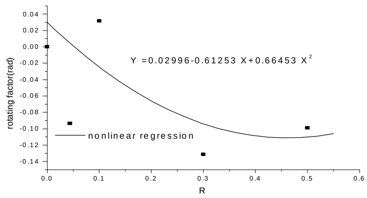

Figure 3: The function of b versus R at $f = 1$.

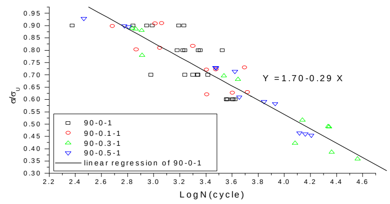

Figure 4: The master curve of Figure1.

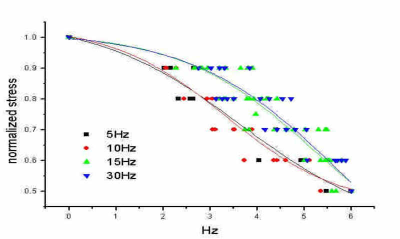

Figure 5: Sigmoid S-N curves of 90˚C/E laminate with different *f* (*f = 5, 10, 15, 30* Hz) and *R = 0.*

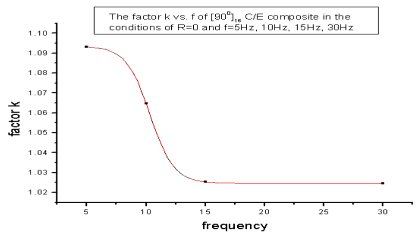

Figure 6: The function of *k* versus *f* at *R = 0*.

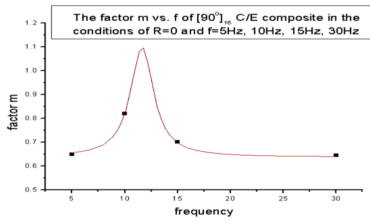

Figure 7: The function of m versus *f* at *R=0*.

5 CONCLUSIONS

Both the straight S-N curves and the sigmoid S-N curves are used in this work to express the fatigue testing data. The straight S-N curves are used to represent the fatigue life of glass/epoxy composites under different stress ratios, and a master curve in the conditions of different stress ratios is established such that the fatigue life at an assigned stress ratio could be predicted. The Sigmoid S-N curves are used to express the full-life fatigue data of carbon/epoxy composites under different stress frequencies. A new sigmoid S-N curve could be also developed for a specific stress frequency, and the full-life fatigue data could be predicted. Comparing the straight and sigmoid S-N curves, the former could just be used in limited life cycles and large errors may occur in the low or high cycles. However, the sigmoid S-N curves could be applied to the whole fatigue life, and the errors in the low or high cycles are small. Hence, the sigmoid S-N curves should be recommended.

ACKNOWLEDGEMENTS

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