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DETERMINATION OF LOAD SEQUENCE EFFECTS ON THE DEGRADATION AND FAILURE OF COMPOSITE MATERIALS

Final Technical Report

NASA Langley Research Center

Grant NSG 1604

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ABSTRACT

This report summarizes the research that was performed under NASA Grant NSG1604, Determination of Load Sequence Effects on the Degradation and Failure of Composite Materials. This grant was initiated in March, 1979, and was extended until its expiration date of August 31, 1980. The Technical Officer of this grant was Dr. T. Kevin O'Brien of the NASA Langley Research Center, Hampton, Virginia 23665.

All of the work that was included in the proposal for this grant has been completed. A theoretical model was established to predict the fatigue behavior of composite materials, with emphasis placed on predictions of the degradation of residual strength and residual stiffness during fatigue cycling. The model parameters were evaluated from three test series including static strength fatigue life and residual strength tests. The tests were applied to two graphite/epoxy laminates, $[\pm 35]_{2s}$ and $[0,90,\pm 45]_{s}$. Load sequence effects were emphasized for both laminates and the predicted results agreed quite well with subsequent verification tests.

Because of the mutual interests of the principal investigators and the technical officer of this grant, the tests on

the $[0,90,\pm 45]_s$ laminates were delayed so that dynamic as well as static stiffness reduction data could be collected. These data were collected by use of a PDP11-03 computer, which performed quite satisfactorily and permitted the recording of a substantial amount of dynamic stiffness reduction data.

INTRODUCTION

Under the sponsorship of this grant, a theoretical model developed under a previous grant, NSG1415, Statistical Characterization of the Fatigue Behavior of Composite Lamina, was extended to include load sequence effects on the predictions of fatigue life, residual strength and residual stiffness of composite laminates. The model was applied to two graphite/epoxy laminates, $[\pm 35]_{2S}$ and $[0,90,\pm 45]_S$. For each laminate the parameters in the model were evaluated from a series of static tensile tests (15-25 tests), fatigue life tests (20-25 tests) and residual strength tests (10-15 tests). Then several verification test series were performed in which the tests were performed under two levels of cyclic loading. A total of approximately 300 tests were performed on these two composite laminates. The agreement between predictions made from the model and actual test results was good in all verification test series.

The results of this work have been well received as indicated by the conference presentations and publications produced under this grant. The results of this work have been presented at two conferences; the ASTM Symposium on Fatigue of Fibrous Composite Materials held in San Francisco (May 22-23, 1979), and the Third International Conference on Composite Materials held in Paris (August 26-29, 1980). The paper presented at the ASTM conference has been published in ASTM STP723, Fatigue of Fibrous Composite Materials, and the paper presented at the Third International Conference on Composite Materials was included in the conference proceedings. In addition to these conference presentations, a paper incorporating some of the analytical work developed under this grant has been published in the Journal of Composite Materials, Vol. 14, 1980, pp. 168-176. Abstracts of these three papers are included with this report. Two additional papers discussing the application of the theoretical model to both laminates have been prepared for publication. In addition, a paper discussing the technique employed for measuring the dynamic stiffness and presenting some of the dynamic stiffness reduction data is being prepared for publication. Since all of these papers have or are expected to be available in the open literature only a brief summary of the results will be included in this report.

PROGRESS

The research sponsored by this grant encompassed an extension of the existing theoretical model as well as the performance of approximately 300 tests to establish the model parameters and verify the accuracy of the theoretical predictions. The developments in each of these areas will be described briefly in this report.

Development of the Theoretical Model

In the previous grant, NSG1415, a three-parameter fatigue and residual strength degradation model

$$R^c(n_1) = R^c(n_0) - \beta^c K S^b (n_1 - n_0) \qquad (1)$$

was developed for unnotched composite laminates under cyclic loading. In Eq. (1), $R(n_1)$ and $R(n_0)$ are the residual strengths at n_1 and n_0 cycles respectively, β is the scale parameter of the ultimate strength, and b, c, K are three parameters to be determined from the test data. The stress range S is defined as

$$S = \sigma_{max} - \sigma_{min} = (1-R)\, \sigma_{max} , \qquad (2)$$

where σ_{max} and σ_{min} represent the maximum and minimum cyclic stress and R is the stress ratio.

For $n_1 = n$ and $n_0 = 0$, Eq. (1) reduces to

$$R^c(n) = R^c(0) - \beta^c K S^b n \tag{3}$$

where the ultimate strength $R(0)$ is a statistical variable assumed to follow a two-parameter Weibull distrubution

$$F_{R(0)}(x) = P[R(0) \leq x] = 1 - \exp\left[-(x/\beta)^{\alpha}\right] . \tag{4}$$

This model was used to calculate the statistical distributions of the fatigue life and the residual strength after a specified number of cycles. It was noted that it is only necessary to evaluate α, β, b, c and K from a limited number of static strength, fatigue life and residual strength tests. Then the model can be used to predict the distributions of fatigue life and residual strength under one or more levels of cyclic loading.

As part of this grant effort a more general degradation model

$$R^v(n) = R^v(0) - f[S_1R(0)]n^{\gamma} \tag{5}$$

was developed in which γ and v were additional parameters and

$$f[S,R(0)] = \frac{1}{\tilde{N}^{\gamma}} \frac{R^v(0) - \sigma^v}{[R^c(0) - \sigma^c]^{\gamma}} . \tag{6}$$

For a given stress ratio, $\tilde{N}$ can can be expressed in terms of the classical S-$\tilde{N}$ curve as

$$KS^b \tilde{N} = 1 \quad . \tag{7}$$

This model was also used to derive expressions for the fatigue life and residual strength distributions under constant and variable amplitude fatigue loadings. The two additional parameters v and γ can be evaluated along with α, β, b, c, K from the same static, fatigue life and residual strength tests.

The revised model possesses the ability to predict the effects of load sequence through (i) the difference in residual strength when fatigue failure occurs (boundary effect) and (ii) the material memory effect with respect to previously experienced loads. It permits the isolation of the memory effect from the boundary effect, with the memory effect represented by the value of γ ($\gamma = 1$ reprents no memory effect). The results of this analysis was applied to both laminates in this test program, with the emphasis placed on load sequence effects due to two levels of fatigue loading.

Experimental Test Program

A test program using coupon specimens of 5208/T300 graphite/epoxy laminates was conducted for the purpose of generating statistically significant test data and verifying the validity of the theoretical model. An independent test program was performed on each of two graphite/epoxy laminates, $[\pm 35]_{2s}$ and $[0,90,\pm 45]_s$, totalling nearly 300 specimens (approximately 150 specimens in each test series).

The testing procedures and approximate numbers of specimens used for each set of tests; i.e., static strength, fatigue life, residual strength tests, etc., were essentially the same for both laminates. The parameters in the theoretical model were first established by performing 45-65 tests, including 15-25 static tensile tests, 20-25 fatigue life tests and 10-15 residual strength tests. For the fatigue tests, the test frequency was 10 Hz and the stress ratio was 0.1. Then additional tests were performed to verify the predicted fatigue life and residual strength distributions resulting primarily from dual level fatigue loadings. The dual level fatigue loadings incorporated one change of load after a specified number of cycles, i.e., a high-low or a low-high loading program. Three verification test series were performed on each laminate.

An additional aspect of the fatigue behavior considered under this grant was the stiffness degradation due to fatigue cycling. Measurements of the static stiffness degradation were made for the $[\pm 35]_{2s}$ laminates but a rather limited amount of data was taken due to the necessity of frequently interrupting the fatigue cycling. In addition, removal and replacement of the extensometer caused problems in obtaining reliable and accurate results.

Two improvements in the testing procedure were subsequently instituted and it was concluded by the technical officer and the principal investigators that the tests on the $[0,90,\pm 45]_s$ should be delayed until these improved techniques could be used. Both improvements contributed significantly to the collection of a greater amount of more accurate stress-strain data. One improvement was the use of a Dual Sensor Strain Transducer (DSST) for measuring the strains in the $[0,90,\pm 45]_s$ specimens. This unit was designed to be retained on composite materials during cyclic loading and led to considerable improvement in the repeatability of the stress-strain data. The second improvement was the purchase and utilization of a PDP11-03 computer for recording the dynamic stress-strain response of these laminates. The computer was programmed to record previously specified stress-strain cycles from which the dynamic stiffness values were calculated. The acquisition and use of this computer resulted in a considerable increase in the data that could be recorded during these fatigue tests. The static and dynamic stiffness data are also being prepared for publication at the present time, so they will not be included in this report.

CONCLUSIONS

A theoretical fatigue model previously developed by the principal investigators has been generalized and used to predict the effect of load sequence on the fatigue life and residual strength degradation of two graphite/epoxy laminates. Previous models have incorporated contributions due to the differences in residual strength at failure (boundary effect), while this research program incorporated the effects of previously applied loads at different load levels (memory effect) into the model.

The model was applied to two graphite/epoxy laminates $[\pm 35]_{2s}$ and $[0,90\pm 45]_s$ to predict load sequence effects on the distributions of fatigue life and residual strength for high-low and low-high fatigue cycling. The model parameters were first evaluated for each laminate by a series of static strength, fatigue life and residual strength tests (40-65 tests). Comparisons were then made between the predicted and actual distributions and the agreement was found to be good for all verification tests. The results of these tests have been prepared for publication.

In addition, static and dynamic stiffness reduction data were generated recorded and reduced with the use of a PDP11-03 computer. The stiffness reduction data is also being evaluated and prepared for publication.

A B S T R A C T S

LOAD SEQUENCE EFFECTS ON THE FATIGUE OF UNNOTCHED COMPOSITE MATERIALS[1]

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ABSTRACT

A comprehensive version of a fatigue and residual strength degradation model previously developed by the authors is proposed. This theoretical model is capable of predicting the statistical distributions of the fatigue life and the residual strength as well as the effect of load sequence, after variable amplitude or spectrum loadings, on these distributions. The model has been verified by the use of existing test data on glass epoxy laminates. It is shown that the correlation between the model and the test results is good.

[1]Presented at the ASTM Symposium on Fatigue of Fibrous Composite Materials and published in ASTM STP 723, American Society for Testing and Materials.

STATISTICAL FATIGUE OF UNNOTCHED COMPOSITE LAMINATES[1]

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ABSTRACT

The complex structure of composite materials has led to the development of a number of statistical models of damage accumulation processes under fatigue loadings. This paper presents a phenomenological approach to fatigue damage accumulation, which incorporates as special cases various statistical models developed previously by the authors and other researchers. The relative merits of each model in predicting the fatigue behavior under various loading programs are discussed in this paper.

On the basis of extensive experimental data, it has been assumed for all of these models that the residual strength is a monotonically decreasing function of the number of cycles of applied loading. All of the model parameters can be evaluated from two sets of test results: (i) a series of ultimate strength

[1]Proceedings of the Third International Conference on Composite Materials, August, 1980, Paris.

tests, and (ii) a series of fatigue tests, including some fatigue life and some residual strength tests. Once the model parameters have been evaluated, the model can predict the statistical distributions of the fatigue life and the residual strength under constant or variable amplitude cyclic loads. A considerable amount of test data generated by the authors and other researchers has been examined to determine the accuracy of this model. Tests have been performed on several different graphite/epoxy composite laminates, including $[0/90/45/-45]_s$, $[\pm45]_{2s}$, $[\pm35]_{2s}$, and $[90/45/-45/0]_s$. The model parameters were evaluated for all of these materials and comparisons were then made between the predicted and actual material response under various types of proof and fatigue loadings. In general, the predicted response has agreed closely with the actual response and several typical examples are presented in this paper.

PROOF TEST AND FATIGUE OF UNNOTCHED COMPOSITE LAMINATES[1]

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ABSTRACT

A comprehensive fatigue and residual strength degradation model has been used to predict the effect of proof loads (or high load) on the statistical fatigue behavior of composite laminates. The validity of the theoretical model is confirmed by the experimental tests results. The correlation between the test results and the theoretical distributions of the fatigue life and the residual strength for composite specimens with or without the effect of proof loads is shown to be very good.

[1]Reprinted from Journal of Composite Materials, Vol. 14(April, 1980), pp. 168-176.