THE CYCLIC FATIGUE BEHAVIOR OF A NICALON/SiC COMPOSITE — N. Miriyala, P. K. Liaw, and C. J. McHargue (University of Tennessee), and L. L. Snead (Oak Ridge National Laboratory).

OBJECTIVE

To develop an understanding of the fabric orientation effects on the monotonic and cyclic fatigue behavior of continuous fiber-reinforced ceramic-matrix composites (CFCCs).

SUMMARY

Cyclic fatigue tests were performed at ambient temperature on a Nicalon/SiC composite to study the effects of fabric orientation on the mechanical behavior. Four-point bend specimens were loaded either parallel or normal to the braided fabric plies. The maximum stresses chosen during the fatigue tests were 60, 70, and 80% of the monotonic strengths, respectively, in both orientations. Specimen failure did not occur in any case even after one million loading cycles. However, it was observed that much of the decrease in the composite modulus occurred in the first few (<10) cycles, and the fabric orientation did not significantly affect the effective modulus or midspan deflection trends.

PROGRESS AND STATUS

Introduction

The interest in continuous fiber-reinforced ceramic-matrix composites (CFCCs) is mainly due to the fact that they fail in a "graceful" manner, unlike the monolithic ceramics. The ability to fail in a non-catastrophic manner is primarily promoted by the large work of fracture required to pull broken fibers out of the matrix against a frictional sliding resistance between the fiber and the matrix, and crack deflection at weak interfaces oriented transversely to the main crack propagation direction [1, 2]. Unidirectional composites exhibit good strength and toughness when the load is applied parallel to the fiber orientation. However, they perform poorly when the load is applied normal to the fibers. Hence, in applications where multi-axial stresses may be encountered, two dimensional (2-D) or three dimensional (3-D) reinforcement is commonly used. One of the common approaches used in the manufacture of 2-D reinforced CFCCs is to make a woven or braided fabric preform and then infiltrate the preform with the matrix. Since the 2-D composites generally suffer from poor interlaminar shear strength, it might be expected that the load bearing capacity of CFCCs, under monotonic and fatigue loadings, may be affected by the orientation of the fabric plies to the loading direction. Previous studies under the current program [3-5] have indicated that the fabric orientation contributed to significant differences in the monotonic and fatigue behavior of Nicalon/alumina composite, while the effects were insignificant for the Nicalon/silicon carbide (SiC) composite. In view of the contrasting role played by the fabric orientation on the mechanical behavior of the two CFCCs investigated, it was decided to perform additional testing and characterization to understand the reasons for the differences observed. Towards this objective, the results from the recently performed cyclic fatigue tests on the Nicalon/SiC composite are presented in this report.

Experimental Details

Material

The Nicalon/SiC composite used in the present study was donated by AlliedSignal Engines. The as-received material was in the form of two plates, approximately 200 × 150 × 2.4 mm, manufactured by DuPont Corporation. A 2-D braided Nicalon fabric was used as the preform, which was first given an interfacial coating of carbon (approximately 0.4 to 0.5 μm) by a chemical vapor deposition (CVD) process, prior to the infiltration of SiC matrix. The SiC matrix was infiltrated by the decomposition of methyltrichlorosilane, in the presence of hydrogen, at 1100 to 1200°C. The nominal fiber volume content in the composite was approximately 40 %.

Flexure testing

Flexure bars were machined from the composite plates using diamond tooling. The ASTM Standard C 1161 configuration requires the specimens to be 50 mm long, 4 mm wide and 3 mm thick. However, in order to objectively study the effects of fabric orientation on the mechanical behavior of the two composites, flexural bars of square cross-section were fabricated. Accordingly. the flexural bars of the Nicalon/SiC composite used in the present investigation were $50 \times 2 \times 2$ mm. Ambient-temperature fatigue tests were performed on a MTS servohydraulic system, equipped with a graphite heating element furnace, that can be used to conduct elevated-temperature tests, up to 2000°C in vacuum or argon.

The cyclic fatigue tests were conducted under load control using a sinusoidal waveform. The loading frequency was 0.5 Hz up to 1000 cycles and then gradually raised to 5 Hz in a multi-ramp mode and maintained at that frequency till the completion of tests. The R-ratio (minimum load/maximum load) used was 0.1, and the fatigue run-out was set at one million cycles, which corresponded to approximately 56 hours of testing. The load and midspan deflection values were recorded at several stages of the fatigue tests to monitor the effective modulus and midspan deflection trends.

During the cyclic fatigue tests, loads were applied to the specimens either parallel or normal to the fabric plies. Accordingly, the specimen configurations were referred to as edge-on and transverse, depending on whether the load was parallel or perpendicular to the fabric plies, respectively (Figure 1).

Results and Discussion

In our previous study on the mechanical behavior of Nicalon/SiC composite [3, 4], it was observed that there was a significant scatter in ultimate strength values in both edge-on and transverse orientations. The flexural strength in the edge-on orientation was 234 ± 27 MPa, while the strength was 241 ± 23 MPa in the transverse orientation. The large scatter in the strength values was attributed to the variation in the porosity content (10 to 20%) and its distribution [5]. Although the average flexural strength was about 7 MPa higher in the transverse orientation than in the edge-on orientation, it may be noted that this difference is insignificant, considering the scatter in the strength values and the porosity content. On cyclic fatigue loading, specimen failure was not observed even when the maximum stress during the tests was greater than 80 % of the monotonic strength, in both orientations. However, it was observed that the effective modulus values decreased upon fatigue loading in all the cases. In the above studies, the load and midspan deflection values were recorded after 1000 loading cycles and beyond and, consequently, there was no understanding of how the load bearing capacity of the composite was affected in the first few loading cycles.

In the present study, flexural specimens, of comparable porosity content (10 to 12%), were subjected to a maximum stress of 140, 165 or 190 MPa, during cyclic fatigue loading, which corresponded to approximately 60, 70 and 80 %, respectively, of the monotonic strength values. The load and midspan deflection values were continuously recorded for the first ten cycles and then at periodic intervals during the

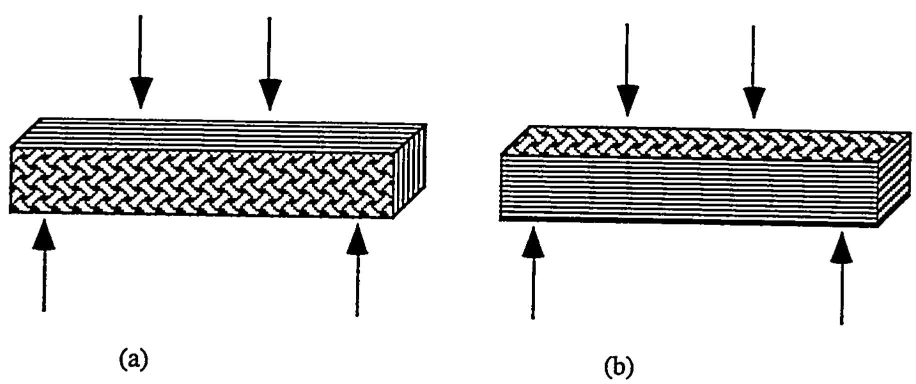

Figure 1. Geometries for testing fiber fabric composites: (a) edge-on and (b) transverse.

remaining part of the test. At least three sets of data were recorded during each log decade of cyclic loading. The slope at a particular point during the fatigue test was normalized with respect to the slope for the first cycle to calculate the "effective modulus" [3,4]. The effective modulus trends in the Nicalon/SiC composite in the edge-on and transverse orientations are presented in Figures 2 and 3, respectively. The increment in midspan deflection (Δd) values are plotted against the number of loading cycles in Figures 4 and 5, respectively, for the edge-on and transverse orientations. From the effective modulus and midspan deflection trends, it appears that the orientation effects are insignificant in the Nicalon/SiC composite.

It can be seen from Figures 2 and 3 that the slope of the load versus midspan deflection values decreased after the first loading cycle in all the samples. Also, the drop in modulus values after the first cycle was higher, as the maximum stress during the fatigue tests was increased, for both orientations. After a relatively steep drop of up to 10% in the first ten cycles, the decrease in effective modulus was less precipitous as the loading continued. At a given fatigue cycle, increasing the maximum stress decreases the effective modulus, which means that the material becomes more compliant, leading to an increase in the specimen deflection (Figures 4 and 5). From Figures 4 and 5 it can also be seen that the midspan deflection values increased steeply in the first ten cycles and more gradually thereafter. Thus, it appears that much of the damage in the composite material occurs in the first ten cycles. According to the current literature, the fatigue in CFCCs occurs due to one or more of the following mechanisms [6]; (i) the interfacial sliding resistance changes as fatigue loading proceeds, as a result of interfacial debonding and sliding, (ii) the strength of the fibers may degrade either due to sliding along the interface by means of an abrasion mechanism, which introduces flaws in the fibers and (iii) fatigue crack growth may occur in the matrix itself in accordance with a Paris law. To understand the progression of damage responsible for the effective modulus trends observed in the present study, metallographically polished flexural specimens were subjected to a maximum stress of 190 MPa and unloaded after 10^1, 10^2, 10^3, 10^4 and 10^5 cycles. It is hoped that the examination of these specimens under a scanning electron microscope, which will be performed shortly, will provide an insight into the damage progression in the material.

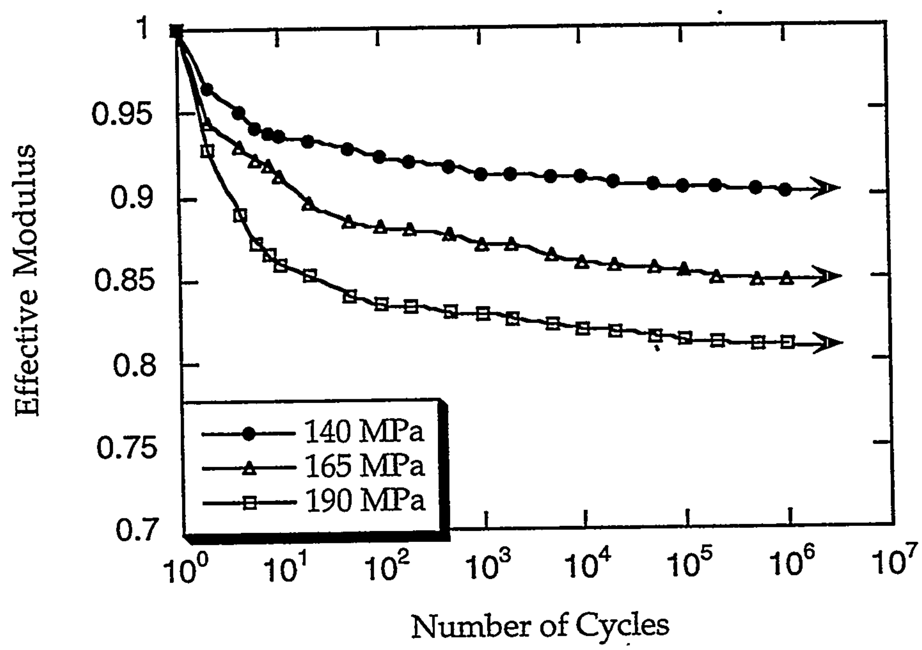

Figure 2. The reduction in effective modulus due to fatigue in the edge-on orientation of the Nicalon/SiC composite.

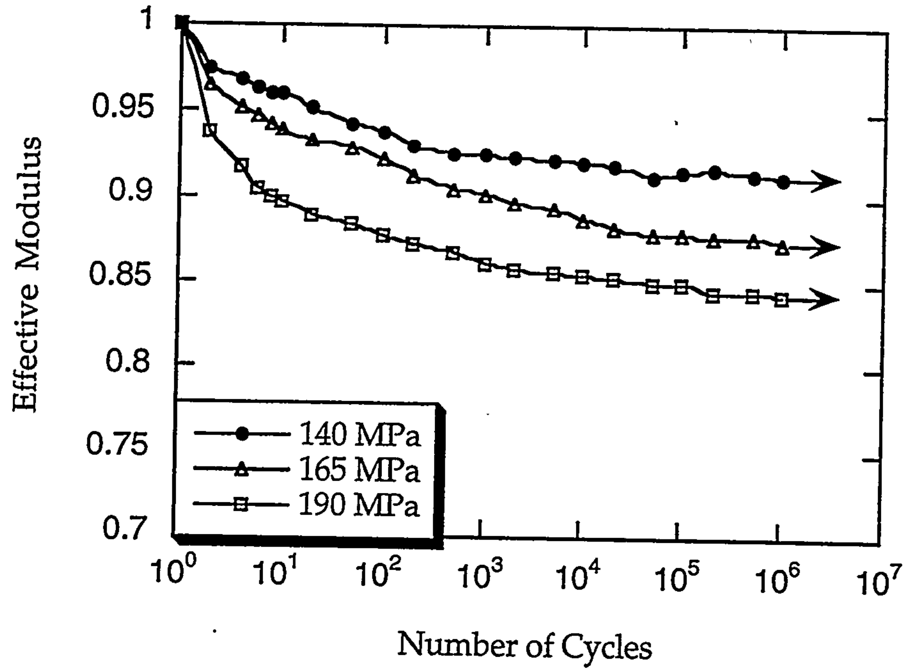

Figure 3. The reduction in effective modulus due to fatigue in the transverse orientation of the Nicalon/SiC composite.

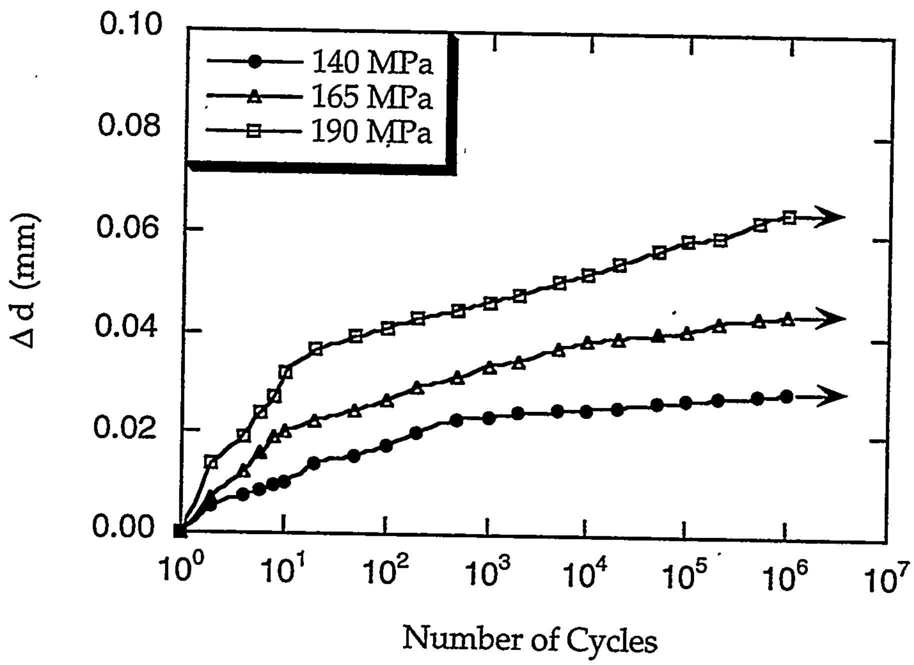

Figure 4. The increase in midspan deflection (Δd) values due to fatigue in the edge-on orientation of the Nicalon/SiC composite.

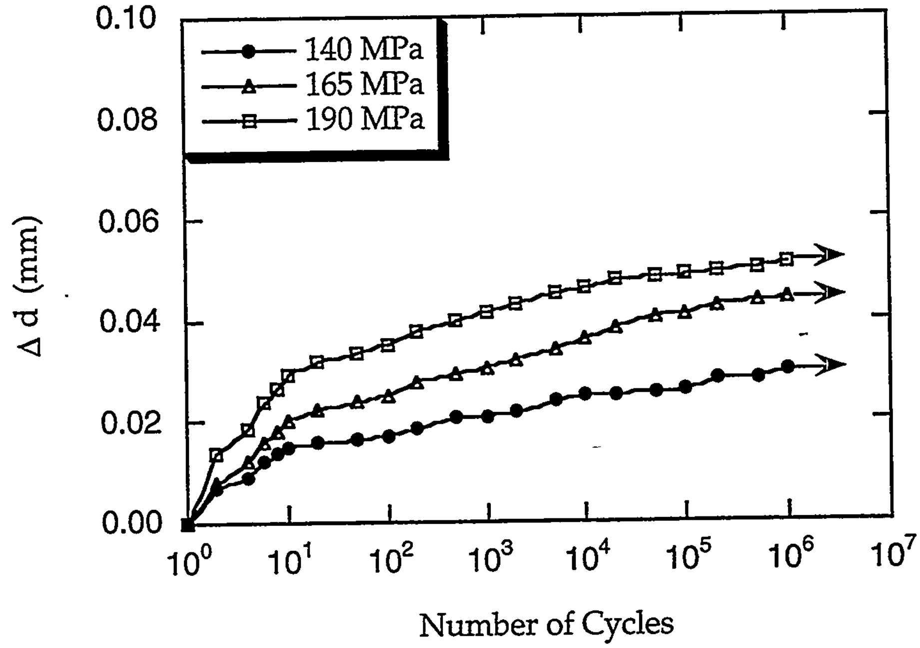

Figure 5. The increase in midspan deflection (Δd) values due to fatigue in the transverse orientation of the Nicalon/SiC composite.

CONCLUSIONS

The monotonic and fatigue behavior of the Nicalon/SiC composite appears to be unaffected by the orientation of fabric plies to the applied loads. The effective modulus of the composite decreased after the first loading cycle in both orientations. After a relatively steep decrease in the modulus values in the first ten cycles, the modulus values decreased more gradually upon further cycling. Consistent with the effective modulus decrease trends, the midspan deflection values increased rapidly in the first ten cycles and then more slowly upon further cycling. It appears that most of the damage in the composite occurs in the first few loading cycles.

FUTURE WORK

The specimens subjected to fatigue loading up to 10^5 cycles will be examined under a scanning electron microscope to gain an understanding of damage progression in the material subjected to cyclic loading. The elevated-temperature monotonic and fatigue behavior of the Nicalon/alumina and Nicalon/SiC composites will be investigated next. Finally, theoretical and numerical modeling will be attempted to help explain the fabric orientation effects on the monotonic and fatigue behavior of CFCCs.

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REFERENCES

1. A. G. Evans, Mater. Sci. Eng. **A107** (1989) 227.

2. A. G. Evans, J. Am. Ceram. Soc. **73** (1990) 187.

3. N. Miriyala, P. K. Liaw, C. J. McHargue and L. L. Snead, Fusion Materials: Semiannual Progress Report for Period Ending December 31, 1995, DOE/ER-0313/19, p 115.

4. N. Miriyala, P. K. Liaw, C. J. McHargue, L. L. Snead and A. S. Fareed, "Effect of Fabric Orientation on the Monotonic and Fatigue Behavior of a Nicalon/Alumina Composite," Ceramic Transactions, 1996, in press.

5. N. Miriyala, "Fabric Orientation Effects on the Monotonic and Fatigue Behavior of CFCCs, " Doctoral Dissertation Proposal, The University of Tennessee, 1995.

6. A. G. Evans, F. W. Zok and R. M. McMeeking, Acta Metall. Mater. **43** (1995) 859.