FATIGUE BEHAVIOR OF NICALON/SiC COMPOSITES - N. Miriyala, P. K. Liaw and C. J. McHargue (University of Tennessee), X. Mao and W. Mao (University of Calgary), L. L. Snead (Oak Ridge National Laboratory) and D. K. Hsu (Iowa State University),

OBJECTIVE

To develop a fundamental understanding of the fatigue damage phenomenon in Nicalon/SiC composites.

SUMMARY

A periodic model using a finite element method (FEM) was developed to predict the effect of porosity on the in-plane and through-thickness elastic stiffness constants of Nicalon/SiC composites. The FEM results indicated that the in-plane moduli values will be higher than the through-thickness moduli values. Also, the predicted values were in close agreement with the ultrasonically measured elastic stiffness constants for the composite material under study.

PROGRESS AND STATUS

Introduction

Ceramics are endowed with many attractive qualities including low density, high hardness, wear resistance, high melting points and the ability to withstand aggressive environments [1-2]. As a result, exciting projections have been made about the ability of advanced ceramics to perform structural functions more efficiently than, and in many cases not possible with, the more traditional metallics. Unfortunately, monolithic ceramics are highly sensitive to process and service related flaws, making them inherently brittle. Continuous fiber reinforced ceramics (CFCCs) or whisker reinforced CMCs, however, can provide a significant amount of toughness as well as avoid catastrophic failure [1-3].

Data on the mechanical properties of the CFCCs is rather scarce owing to the experimental difficulties in performing the mechanical tests and often the high material costs. Even more scarce is the theoretical modeling work on mechanical behavior of woven fiber reinforced ceramic matrix composites. To our knowledge, only a few attempts have made so far to predict the moduli of woven fabric composites [4-7]. Towards this direction, the FEM study presented in this report augments the recent efforts to predict the mechanical behavior of a woven fiber composite from a knowledge of elastic constants of the constituents that make up the composite.

Theoretical Modeling

Metallographic examination of the composite revealed that there are two major types of porosity in the Nicalon/SiC composite, viz., porosity at the fiber tow intersection and interlaminar porosity. The extent of interlaminar porosity was found to be greater than the porosity at the fiber tow intersection [4-7]. A finite element model based on periodic microstructure was hence developed to estimate the effect of porosity on the elastic properties of the Nicalon/SiC composites. The representative unit cell shown in Figure 1 was used to model the two major types of porosity and to predict in-plane and through-thickness elastic moduli of the Nicalon/SiC composite.

For stress and strain analysis by the finite element method (FEM), generally the equations of equilibrium are obtained from the principle of minimum total potential energy, and are expressed as

$$[K]\{U\} = \{P\}$$

where [K], {U} and {P} represent total structural stiffness, nodal displacements and applied loads, respectively. After solving for the nodal displacements, the stresses and strains can be evaluated from the following equations.

$$\{\varepsilon\} = [B]\{U\}$$

$$\{\sigma\} = [C][B]\{U\}$$

where $\{\varepsilon\}$, $\{\sigma\}$, {B} and [C] are strain vector, stress vector, strain-displacement relationship matrix and material property matrix, respectively.

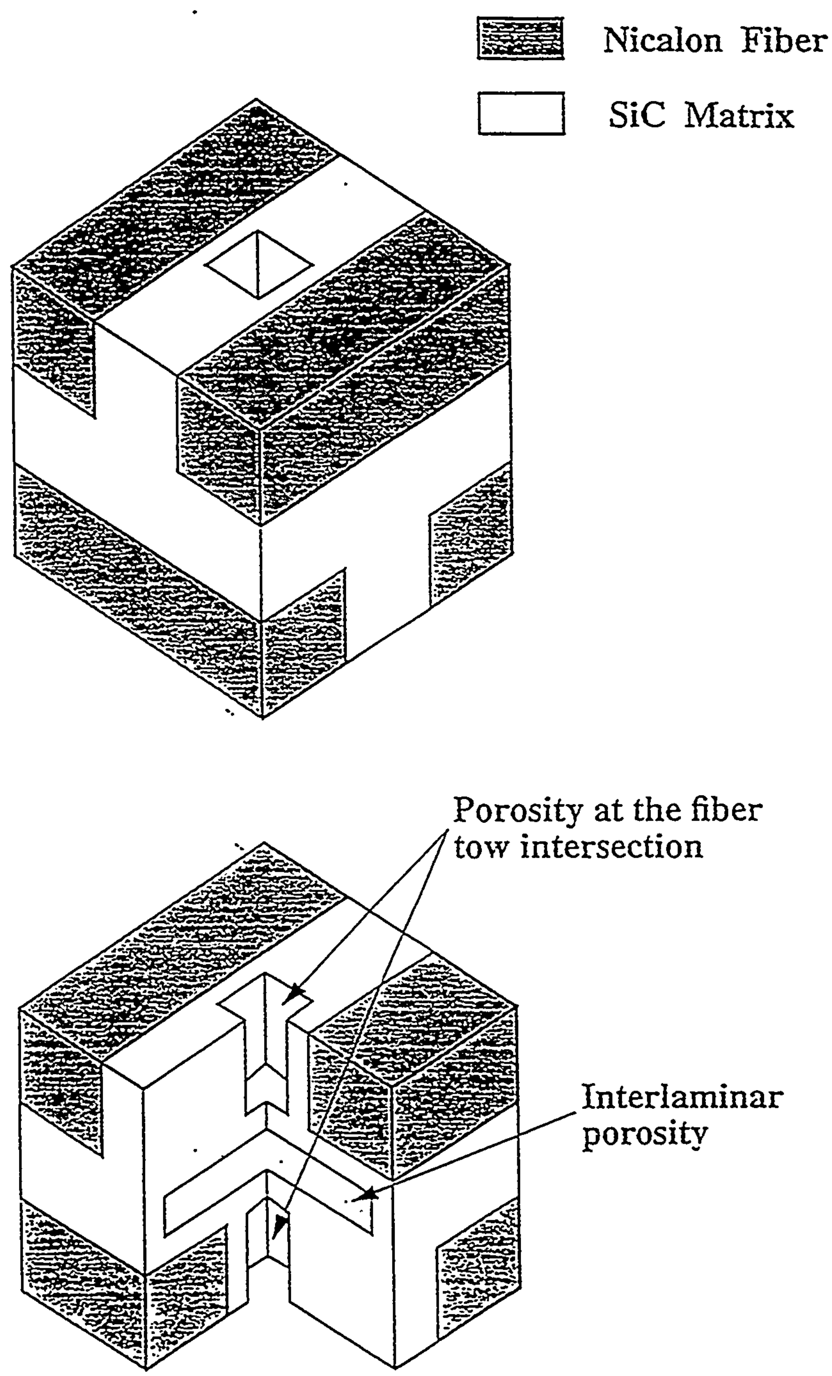

Figure 1. Representative unit cell of Nicalon/SiC composite used in the FEM study

With $\{\varepsilon\}$ and $\{\sigma\}$, the strain energy of the structure U can be expressed as

$$U = \frac{1}{2}\int_V \{\varepsilon\}^T\{\sigma\}dV$$

where V is the volume of the structure.

The method of evaluating the equivalent moduli of the composite is as follows:

1. Calculate the strain energy of a composite material unit by a finite element method

$$U_1 = \sum_{i=1}^{n}\int_{V_i} \{\varepsilon\}^T\{\sigma\}dV$$

where V_i is the volume of each element and n the number of total elements. The reason for using the finite element method is that it is always possible to mesh the unit in such a way that there is only one type of material in each element.

2. Consider a homogeneous material unit with the same dimensions of the composite material. Apply the same loading and boundary constraint conditions on the homogeneous material unit as on the composite material unit. Then, the strain energy will be

$$U_2 = \frac{1}{2}\int_V \{\varepsilon\}^T\{\sigma\}dV = \frac{1}{2}\int_V \{\varepsilon\}^T[C]\{\varepsilon\}dV$$

By choosing specific loading and boundary constraint conditions, we can make only one ε_i in the $\{\varepsilon\}$ vector remain non-zero. Then,

$$U_2 = \frac{1}{2}\int_V C_{ii}\varepsilon_i^2 dV$$

For a homogeneous material, C_{ii} is same everywhere. Therefore

$$U_2 = \frac{C_{ii}}{2}\int_V \varepsilon_i^2 dV$$

3. Assume that the equivalent homogeneous unit will contain the same amount of strain energy as its corresponding composite material unit when they are subjected to the same loading and boundary constraint conditions; that is

$$U_1 = U_2$$

Thus, we finally have

$$C_{ii} = \frac{U_1}{\frac{1}{2}\int_V \varepsilon_i^2 dV}$$

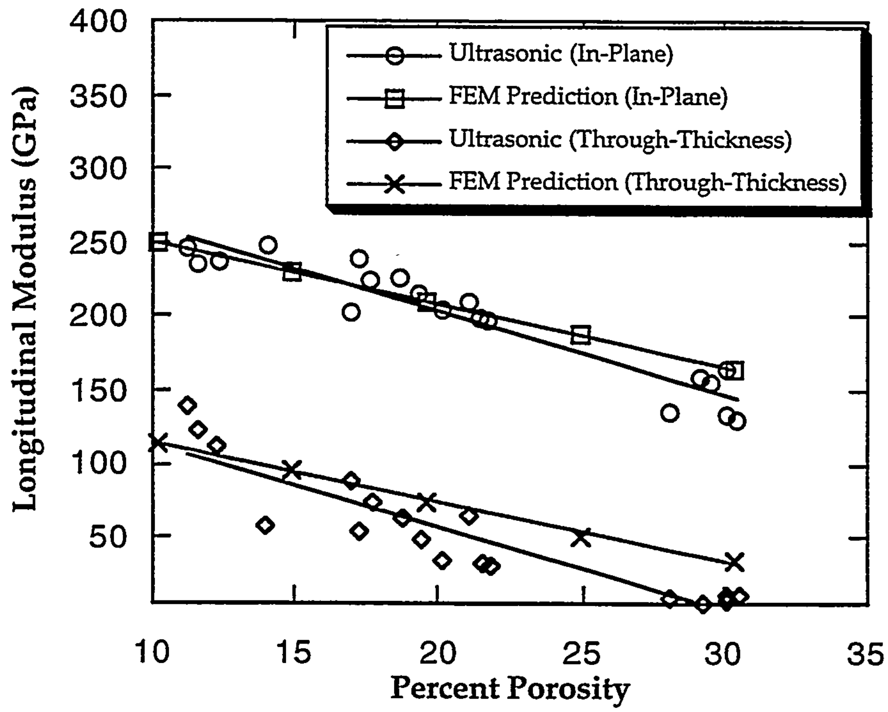

Figure 2. Comparison of ultrasonically measured and FEM predicted longitudinal moduli values in Nicalon/SiC composite

To calculate the moduli of the composites, the following input data were used [8]; the shear modulus and Poisson's ratio of the Nicalon fiber were 80 GPa and 0.12, respectively, and those of the matrix were 146 GPa and 0.2. The predicted in-plane and through thickness

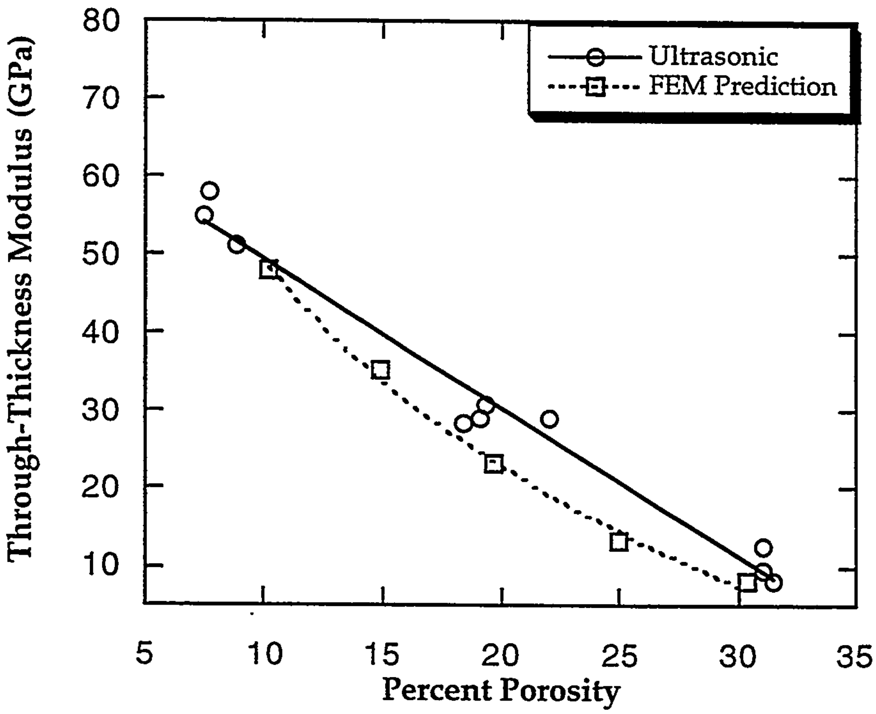

Figure 3. Comparison of ultrasonically measured and FEM predicted shear moduli values in Nicalon/SiC composite

values are plotted in Figures 2 and 3 along with the experimental results. The FEM analysis predicted that (i) the in-plane longitudinal modulus of the composite will be higher than the through-thickness modulus, (ii) the shear modulus will be lower than the longitudinal modulus and (iii) that increased porosity content in the material significantly lowers both longitudinal and shear moduli of the composite. It is evident from Figures 2 and 3 that there is a good agreement between the theoretically predicted values and ultrasonically measured elastic moduli.

FUTURE WORK

(i) Flexural fatigue testing of specimens using different R-ratio (minimum stress/maximum stress) values at ambient as well as elevated temperatures.
(ii) Fractography of the specimens to assess the damaging mechanisms that govern the fatigue and fracture behavior of the Nicalon/SiC composites.
(iii) Theoretical modeling of the fatigue damage mechanisms in CFCCs.

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