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Effect of fiber fabric orientation on the flexural monotonic and fatigue behavior of 2D woven ceramic matrix composites

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ABSTRACT

The effect of fiber fabric orientation, i.e., parallel to loading and perpendicular to the loading axis, on the monotonic and fatigue behavior of plain-weave fiber reinforced SiC matrix laminated composites was investigated. Two composite systems were studied: Nextel 312 (3M Corp.) reinforced SiC and Nicalon (Nippon Carbon Corp.) reinforced SiC, both fabricated by Forced Chemical Vapor Infiltration (FCVI). The behavior of both materials was investigated under monotonic and fatigue loading. Interlaminar and in-plane shear tests were conducted to further correlate shear properties with the effect of fabric orientation, with respect to the loading axis, on the orientation effects in bending. The underlying mechanisms, in monotonic and fatigue loading, were investigated through post-fracture examination using scanning electron microscopy (SEM).

1. Introduction

Continuous fiber ceramic composites (CFCCs) are being used in high temperature and structural applications [1–5]. CFCCs are quite advantageous because they are lightweight structural materials that exhibit a much higher resistance to high temperatures and aggressive environments than metals and other conventional engineering materials. Monolithic ceramics, for example, are very brittle due to their high sensitivity to process and service-related flaws. Due to their low toughness, these materials fail catastrophically. One of the major advantages of continuous fiber ceramic composites (CFCCs) or whisker reinforced ceramic matrix composites (CMCs) is that these materials fail in a non-catastrophic manner [2,4].

Most of CFCCs are reinforced with two dimensional (2D) fiber fabrics. As in classical laminated composites, the fiber fabrics can also be aligned at different angles to obtain quasi-isotropic behavior in the plane. In CFCCs fabricated by chemical vapor infiltration (CVI), it is common to have residual porosity within fiber bundles and between layers of the composites. When CFCC beams are tested in bending, with the loading direction normal to the layers, delamination between the layers has been observed [4]. The bending behavior of CFCC laminates with the loading direction parallel to plane of the layers has not been investigated. This orientation effect has been investigated in notched metallic laminated composites under impact conditions by the Charpy test [6]. The authors chose to designate the geometry where the plies were perpendicular to the loading direction as crack arrester, and the geometry where the plies were parallel to the load as crack divider. In CFCCs however, due to the subcritical damage mechanisms, we cannot make the assumption that a single crack is propagating through the composite in a self-similar manner (i.e., only one principal crack is propagating through the material). Therefore, we designated the geometries, where loadings are perpendicular and parallel to the laminate layers, as transverse and edge-on, respectively, Fig. 1.

The objective of this work was to obtain insight into the effect of fiber fabric orientation on the monotonic and fatigue behavior of plain-weave fiber reinforced SiC matrix laminated composites, processed by CVI. Two composite systems were studied: Nextel 312 (3M Corp.) reinforced SiC and Nicalon (Nippon Carbon Corp.) reinforced SiC, both fabricated by Forced Chemical Vapor Infiltration (FCVI). The behavior of both materials was investigated under monotonic and fatigue loading. Interlaminar and in-plane shear tests were conducted to further correlate shear properties with fabric orientation. The underlying mechanisms, in monotonic and fatigue loading, were investigated through post-fracture examination using scanning electron microscopy (SEM).

2. Materials and experimental procedure

The composites used in this study were processed by CVI. Nextel 312 and Nicalon fibers were used as reinforcements for the

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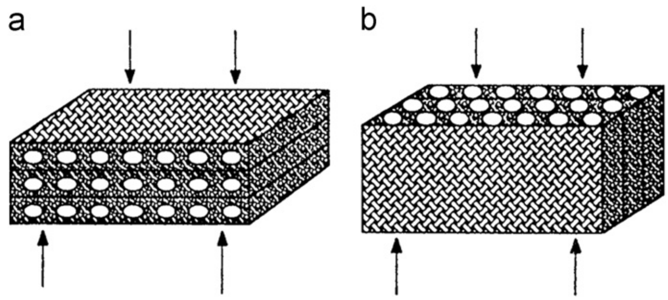

Fig. 1. Geometries for testing plain-weave fiber reinforced SiC matrix composites: (a) transverse and (b) edge-on.

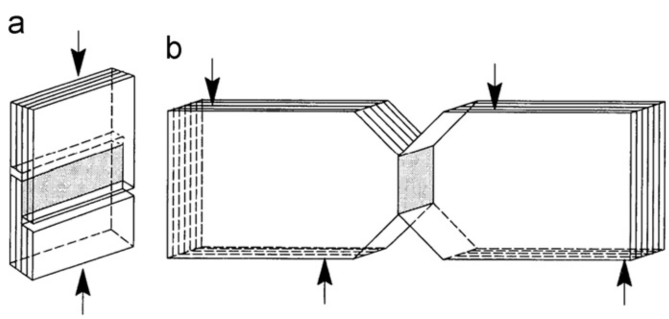

Fig. 2. Schematic of specimen dimensions and testing configuration for (a) double-notched interlaminar shear and (b) in-plane shear experiments.

CVI SiC matrix. Nextel 312 is an oval polycrystalline fiber with minor and major axes lengths of 8 and 12 μm, respectively, composed of Al_2O3, SiO_2, and B_2O3. CG-Nicalon is a circular amorphous fiber, about 15–18 μm in diameter, composed of Si, C, and O. The fibers were woven into a plain-weave fabric. Before infiltration, the fabric was coated with 0.3 μm thick pyrolitic carbon, by chemical vapor deposition. The coating was used to provide the weak necessary for crack deflection and fiber pullout in these composites. The Nextel-baesd composites were fabricated at Oak Ridge National Laboratory (ORNL) by Forced Chemical Vapor Infiltration (FCVI). Here a thermal gradient in the perform is used to obtain faster infiltration. Details of FCVI are given elsewhere [3]. The Nicalon reinforced composites were processed at BF Goodrich by isothermal CVI.

The Nextel reinforced SiC composite was fabricated in disk form to a final diameter of 24 cm and thickness of 1.25 cm. Nextel plain weave [0/90] fabric was stacked at a fabric orientation of [0/30/60]. Therefore, the orientation of the fibers was [0/90], [30/120], and [60/150]. The composite had 10 plies per 0.25 cm and a nominal fiber volume fraction of 40%. The Nicalon reinforced composite had a simpler stacking sequence of [0/90] for all plies. The number of plies per unit thickness was the same and the coating applied to the fiber fabric was identical to that deposited on Nextel fibers. The composite plate had dimensions of 21 cm × 21 cm and a thickness of 0.35 cm. Density measurements were obtained using Archimedes principle.

Flexure bars were cut from the composite disks and plates to the following dimensions: length, 50 mm; width, 3 mm; and thickness, 3 mm (∼12 plies/specimen). The commonly used standard calls for a width of 4 mm, but in order to compare the two geometries in a fair manner, the width and thickness were cut to the same dimension. Monotonic tests were conducted in four-point flexure with major and minor spans of 40 mm and 20 mm at a constant cross-head displacement rate of 0.5 mm/min. 4–5 samples per orientation, per composite, were tested. Flexural fatigue tests, also in four-point flexure, were done in load control using a triangular waveform at a frequency of 0.33 Hz. 2–3 specimens per stress level were conducted. A constant R ratio ($\sigma_{min}/\sigma_{max}$) of 0.02 was used. Specimens that survived 10^5 cycles were fractured under monotonic loading to obtain the post-fatigue strength. Fracture surfaces were examined in a SEM.

In order to understand the mechanisms in monotonic flexure for both geometries, interlaminar and in-plane shear strength experiments for both composites were conducted. Double notched specimens were used for interlaminar shear testing, Fig. 2. Specimens were notched with a thin diamond blade. In-plane shear strengths were obtained from V-notched specimens using the modified Iosipescu geometry for shear testing [7], also shown in Fig. 2.

3. Results and discussion

3.1. Monotonic behavior

Higher densities were obtained in Nextel/SiC composite compared to Nicalon/SiC. In Nextel/SiC composite, overall density was highest at the bottom of the plate, where the reactant gases entered the preform during infiltration. The top layer was slightly less dense than the bottom, but it was denser than the middle of the plate. This is in contrast with observed results of smaller, denser preforms infiltrated by FCVI, which show the densest layer at the top and the least dense layer at the bottom. We hypothesize that the density was highest in the center of the plate because of more holes in the graphite holder which allowed a higher fraction of the reactant gases to come into contact with the fibrous preform. Gradients in density through the thickness of the plate in the Nicalon reinforced SiC composite were not observed because of the relatively small infiltration thickness. Overall densities were 85–90% in Nextel/SiC of the theoretical density and 70–75% of theoretical in Nicalon/SiC. The lower densities in Nicalon/SiC can be attributed to high reactant gas pressure, which, while reducing infiltration time, caused the matrix to infiltrate as an overcoat of the fiber bundle, instead of within the bundle.

The laminate stacking sequence of the Nextel/SiC composite was also more beneficial for infiltration. Recall that the Nextel plain-weave cloth was stacked in increasing 30° increments, so that the fibers were arranged in [0/90], [30/120], and [60/150], respectively. The Nicalon/SiC composite was stacked with continuous [0/90] layers. The advantage of the Nextel/SiC stacking sequence is that as the reactant gases passed through the holes of a given fabric ply, the gases immediately came into contact with fibers of the next ply because of the rotation scheme. In the Nicalon/SiC composite, the gases that went through the holes in a given ply went through the thickness of the composite because of the identical stacking sequence in all plies.

Monotonic loading flexural tests showed differences in the behavior of the two geometries. Stress values were determined using beam theory assuming symmetric tension-compression elastic behavior. In the edge-on orientation of the Nextel composite, the proportional limit stress, σ_{pl}, was around 80 MPa and the ultimate stress was 170 ± 18 MPa, Fig. 3(a). The transverse specimen also had a similar σ_{pl} of 80 MPa, but showed a lower ultimate stress of 154 ± 17 MPa. Similar results were obtained in the Nicalon composite where both orientations showed σ_{pl} of 150 MPa, but the edge-on orientation ultimate strength was 330 ± 50 MPa compared to 300 ± 18 for transverse, Fig. 3(b). Thus, we can see that the proportional limit is an intrinsic property of the matrix material and not really dependent on fabric orientation.

The higher strengths obtained in both orientations of Nicalon/SiC over Nextel/SiC composite were due to the much higher