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Effect of on-axis tensile loading on shear properties of an orthogonal 3D woven SiC/SiC composite

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Abstract

The present study examines in-plane and out-of-plane shear properties of an orthogonal 3D woven SiC fiber/SiC matrix composite. A composite beam with rectangular cross-section was subjected to a small torsional moment, and the torsional rigidities were measured using an optical lever. Based on the Lekhnitskii's equation (Saint–Venant torsion theory) for a orthotropic material, the in-plane and out-of-plane shear moduli were simultaneously calculated. The estimated in-plane shear modulus agreed with the modulus measured from ±45° off-axis tensile testing. The effect of on-axis (0°/90°) tensile stress on the shear stiffness properties was also investigated by the repeated torsional tests after step-wise tensile loading. Both in-plane and out-of-plane shear moduli decreased by about 50% with increasing the on-axis tensile stress, and it is mainly due to the transverse crack propagation in 90° fiber bundles and matrix cracking in 0° fiber bundles. It was demonstrated that the torsional test is an effective method to estimate out-of-plane shear modulus of ceramic matrix composites, because a thick specimen is not required.

Keywords: Ceramic matrix composites; Matrix cracking; Transverse cracking; Finite element analysis

1. Introduction

It is now well understood that continuous fiber ceramic matrix composites (CMCs) exhibit nonlinear stress–strain behavior under tensile loading as a result of multiple microcracking and fiber fragmentation. An overview of CMC mechanical properties has been provided by Evans and Zok [1]. For unidirectional CMCs, the change in stiffness due to multiple matrix cracking has been estimated by elastic analysis based on the Lame problem [2], and shear-lag analysis [3]. In cross-ply composites, this change also involves initial cracking in the transverse (90°) plies as tunneling cracks [4–7]. Subsequently, transverse cracks penetrate the longitudinal plies as the load is increased. Based on the energy criterion and finite element analysis, transverse crack propagation in cross-ply brittle matrix composites has been analyzed [6,7]. Shear-lag analysis is often used to estimate transverse crack propagation within polymer matrix composites [8], and this method has also been applied to an orthogonal 3D woven CMC as well as cross-ply CMCs [9].

The effect of transverse crack on shear stiffness degradation has been investigated for polymer matrix composites. For example, Kobayashi et al. [10] investigated the effect of on-axis tensile loading on degradation of in-plane and out-of-plane shear moduli of cross-ply carbon fiber/epoxy composites. The experimental results

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were compared with the numerical results based on Tsai–Daniel model [11], Hashin model [12], and Gudmundson–Zang model [13], and conservative stiffness degradation as a function of transverse crack density was predicted by these models.

Some researchers experimentally investigated the degradation of in-plane shear modulus in CMCs by off-axis tensile test and V-notched shear (Iosipescu) test [14,15], and the effect of in-plane shear stress on in-plane shear stiffness degradation has been understood. However, the effect of on-axis loading on the in-plane and out-of-plane shear properties of CMCs have not been revealed yet.

For evaluating the effect of on-axis loading on shear properties, the shear modulus of a composite which has microscopic damages caused by on-axis tensile stress should be measured. However, it is difficult to make *thick* CMC specimens because of difficulty in processing. Standard test methods such as rail-shear method (ASTM-D4255), off-axis tensile test method (ASTM D3518), V-notched shear (Iosipescu) method (ASTM C1292) are not applicable for measuring out-of-plane shear modulus of *thin* CMC specimens.

A unique test method for measuring out-of plane shear modulus has been provided by Ishikawa et al. [16]. They applied a torsional test for estimating out-of plane shear modulus of a unidirectional carbon fiber/epoxy composite based on Lekhnitskii's torsion theory [17]. Tsai et al. also presented a closed-form solution for a composite laminate under torsion in terms of the lamination geometry, and the experimental methodology to determine the three principal shear moduli by measuring surface and edge strains in twisted prismatic coupons [18]. The torsional test is useful to estimate out-of plane shear properties, because a thick specimen is not required for the experiment.

In this study, the in-plane and out-of-plane shear properties of an orthogonal 3D woven SiC fiber/SiC matrix composite were evaluated by torsional test of a rectangular cross-section beam. The experimental results were compared with numerical results by finite element analysis (FEA). Furthermore, the effect of on-axis tensile loading on shear modulus degradation of the SiC/SiC composite was also examined.

2. Torsional test methodology

Based on Lekhnitskii's torsion theory for an orthotropic material, Swanson established a torsion theory for composite laminated rectangular rods [19]. However, it is difficult to expand this theory for an orthogonal 3D woven composite. Therefore, Lekhnitskii's torsion theory is directly applied, assuming an orthogonal 3D woven composite as a uniform orthotropic material.

A schematic drawing of a torsion beam is shown in Fig. 1. A specimen consists of a rectangular cross-section beam with dimensions b (width) by h (thickness) in y and z directions, with L (length) in x direction. The coordinate x is parallel to a material axis. For an orthotropic material twisted about an axis parallel to the material direction (x direction) with torsional moment M_t, the torsional rigidity GJ ($=M_t/\omega$) is given by [17]:

$$GJ = G_{xy}\beta(c)bh^3,$$
$$\beta(c) = \frac{32c^2}{\pi^4}\sum_{k=1,3,5\ldots}^{\infty}\left\{1-\frac{2c}{k\pi}\tanh\left(\frac{k\pi}{2c}\right)\right\},$$
$$c = \frac{b}{h}\sqrt{\frac{G_{zx}}{G_{xy}}}, \quad (1)$$

where ω is a twist angle per unit length, G_{xy} and G_{zx} are in-plane and out-of-plane shear moduli. As this equation is based on Saint–Venant torsion, so-called "warping effects" are neglected.

Ishikawa et al. [16] investigated the effect of warping-torsion on the torsional rigidity of a unidirectional composite beam, and revealed that torsional rigidity increases under the warping torsion. For an actual experiment, specimen grip areas shown in Fig. 1 are constrained for applying torsion moment and for fixing specimen with a fixture. Therefore, the effect of warping on torsional rigidity was preliminarily investigated by finite element analysis (FEA). A commercial FEA code ABAQUS was used for the calculation.

The numerical results under the condition of $L/H = 26.7$, and $G_{xy}/G_{zx} = 2$ are shown in Fig. 2 for b/h of 1, 2, 4, and 8. ω_n and ω_a are twist angles per length calculated by FEA and Lekhnitskii's torsion theory (Eq. (1)), respectively. While the grip areas are assumed to constrain the warping deformation strictly in the calculation, these boundary conditions are much stricter than those in an actual experiment. The

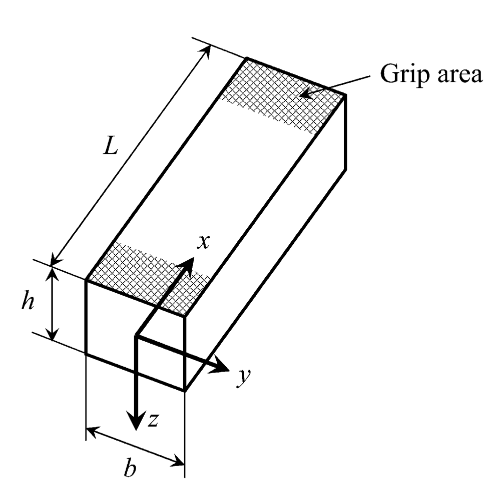

Fig. 1. Specimen configuration and coordinate system for torsional test.