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The effect of transverse damage on the shear response of fiber reinforced laminates

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ABSTRACT

Matrix damage, in the form of cracks parallel to the fiber due both to in-plane tensile loading perpendicular to the fibers and to in-plane shear loading, is a common failure mode for composite structures, yet little is known concerning their interaction. Past work has focused on experimental and analytical studies of axial and transverse stiffness reduction due to matrix cracks. By comparison, there is relatively little experimental work addressing shear modulus degradation from matrix damage. In this paper, a modified Isoipescu coupon is proposed to study the shear modulus degradation due to loading perpendicular to the fibers direction. The layup and coupon geometry were selected in a way that controls the severity of the damage and allows the measurement of shear and transverse stiffness degradation in the same coupon. The proposed method showed good agreement with results from tubular specimens and has advantages of simplified specimen fabrication using standard test fixtures. The results provided the first experimental comparison of shear modulus reduction, from transverse damage, to the predictive models. The results were compared with existing analytical and numerical models which over predicted the observed shear modulus reduction.

1. Introduction

Failure analysis of composite materials is complex because of their anisotropic nature. The increasing application of composite materials has strengthened the need to understand reliability and damage characterization in design. The result of a worldwide composite failure theory examination showed that existing theories are incapable of predicting the nonlinear deformations observed experimentally where the behavior was dominated by the matrix [1]. Matrix cracking is usually the first dominant damage mode that occurs in fiber reinforced composite materials.

Characterizing and understanding the nature of material degradation has been the subject of numerous studies. Laminate progressive failure models depend on a failure criterion for the first ply failure and a material degradation model to describe hardening or softening after first ply failure. Failure in the fiber direction is usually catastrophic, while degradation factors are applied when failure occurs in the matrix. This work considered matrix cracks parallel to the fiber due to loading perpendicular to the fibers, hereafter refers as transverse loading, and studied the effect of matrix cracks on the transverse and shear stiffness. The transverse stiffness reduction can be predicted using analytical or semi-analytical solutions. Analogous models for the shear modulus reduction have been developed; however, these models have not been experimentally verified.

Hashin [2,3] analyzed the stiffness reduction of cracked cross ply laminates by a variational method on the basis of the principle of minimum complementary energy. Results were given for axial stiffness, Poisson's ratio and shear modulus of a $[0/90_3]_s$ glass epoxy laminate. The comparison with experimental data was done for axial stiffness reductions only, which showed good agreement. Tan and Nuismer [4] and Nuismer and Tan [5] proposed an analytical solution based on a shear lag theory for progressive matrix cracking in a composite laminate. The closed form solutions were obtained for laminate stiffnesses and Poisson's ratio as function of crack density. The model was compared with experimental data for axial stiffness and Poisson's ratio.

El Meiche et al. [6] used a modified shear lag theory to predict stress distribution and stiffness reduction in hybrid cross-ply laminates with transverse matrix cracking. This model considered the normal stress transfer through the adhesive layer. The theoretical results were compared with experimental data in the axial direction. Zhang et al. [7] proposed a semi-analytic model for predicting the thermoplastic property degradation in general symmetric

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laminates with uniform ply cracks in some or all of the 90° layers. The application of the methodology was shown by numerical examples of material stiffness degradation. The axial stiffness and Poisson's ratio were compared with experimental data while the shear modulus reduction was compared with numerical results from other models in the literature. Berthelot [8] developed a generalized approach to evaluate stress distribution and stiffness reduction for cross ply laminates. He compared his results with finite element analysis. None of the aforementioned compared the effect of matrix damage on shear modulus with experimental data, leaving their suitability to this loading condition unknown.

For axial and transverse stiffness properties and their degradation, there are well documented experimental techniques that are widely used. The details of measuring these material properties can be found in ASTM standards [9–12]. The testing of shear properties, and particularly the shear modulus for fiber reinforced composite materials, has been a controversial topic. There are various standard methods for shear modulus measurement: the ±45° coupon tension test [13], the off-axis tension test, the Arcan test, the Iosipescu shear test [14], the rail shear test [15], and the torsion test [16]. The two more popular of these methods are the Iosipescu and the ±45 coupon tension test methods. These methods are popular because of relative ease of specimen fabrication and testing. The torsion test is, nevertheless, the most accurate method to measure shear modulus, due to its uniform stress sate and absence of free edge effects. Knops and Bogle [17] compared shear modulus degradation of the tubular specimens with Puck's failure theory. He used a $[\pm 45/89.45_3]_s$ glass–epoxy laminate made by filament winding. These specimens were loaded in the axial direction to form cracks parallel to the fiber after which pure torque was applied to determine the shear modulus reduction. In contrast to that assumed by Puck, the results showed that matrix cracks have a larger effect on transverse stiffness than shear stiffness. Knops and Bogle [17] did not compare their measured material stiffness degradation with predictive models. However, given the difficulty in preparing and testing tubular specimens, Knops et al. appears to be the only experimental work of shear modulus reduction from transverse damage.

In the following, a modified Iosipescu coupon is proposed to study the evolution of the damage due to shear and transverse loading and their mutual effects. The layup and coupon geometry were selected to control the severity of damage and allow the measurement of shear and transverse stiffness degradation experimentally. A finite element simulation was performed to investigate the stress and strain distribution in the critical plies.

2. The experiment design

Among the standard shear tests, only the Iosipescu and cylindrical coupons can induce cracks under transverse and shear loading in the same coupon. When loaded in a tension–torsion load frame, a cylindrical coupon can induce transverse and shear stress simultaneously. The Isoipescu coupon can create these stress states independently by loading in shear (using the Isoipescu fixture) or in tension (using standard tension grips). Fig. 1 shows the Iosipescu and torsion coupons under axial or shear load. In this work the Iosipescu coupon was modified to introduce different crack densities under transverse or shear loading.

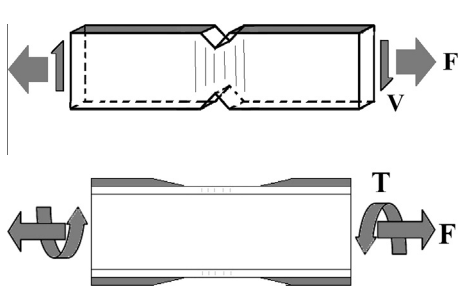

Fig. 1. The Iosipescu and torsion coupons cross-section under axial/shear load.

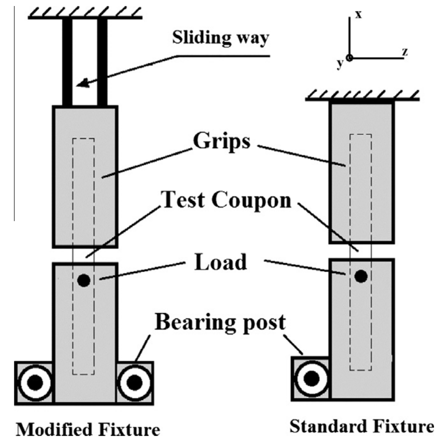

Fig. 2. Top view of the standard and modified ASTM D5379 shear test fixtures.

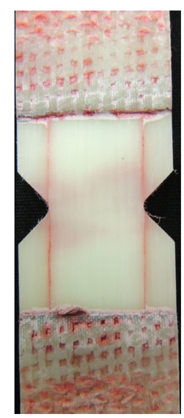

Fig. 3. The Iosipescu coupon loaded to 18 kN.

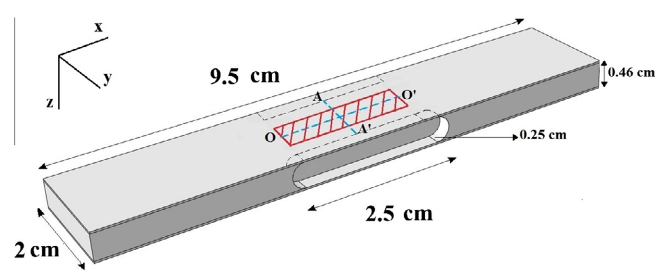

Fig. 4. Slotted coupon geometry.

In the standard Iosipescu shear fixture, one end of the coupon is fixed, while the other end is constrained to displace in the y direction. As shown in Fig. 2, the constraint in the y direction in the standard fixture is offset from the longitudinal axis of the coupon in the x direction. Thus, if the length of the coupon in the x direction changes during the test, due to the Poisson effect, the offset constraint induces bending. While pure shear should not cause a length change, the notches and grips induce normal stresses, in the x direction, which can cause the coupon length to change [18]. In the following a modified Iosipescu shear fixture was used,