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Free-edge effect on the effective stiffness of single-layer triaxially braided composite

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ABSTRACT

Free-edge effect is known to play an important role in the failure of triaxially braided composites, especially under transverse tension loading conditions. However, there is little understanding available regarding the free-edge effect on the elastic property of the material. The emphasis of the present study is to examine the impact of the free-edge effect on the effective elastic response of a single-layer triaxially braided composite. Transverse tension straight-sided coupon specimens with various widths are tested and analyzed. The experimental results demonstrate an obvious increase in the tangent modulus and failure strength as the specimen width increases. The surface out-of-plane displacement contours present a continuous out-of-plane warping behavior distributed periodically along the free edges in an antisymmetric way. A meso-scale finite element model is utilized to study the coupon specimens; it is found to correlate well with the experimental data in predicting elastic properties and out-of-plane warping behavior. The results indicate that free-edge effect is an inherent factor of the antisymmetric braided architecture of bias fiber bundles. By conducting a dimensional analysis, the relationships between effective moduli and specimen width are quantified using Weibull equations; this method could potentially be used to predict the material properties of large structural components using small-scale test data.

1. Introduction

Triaxially braided composites represent a class of textile composites in which two bias yarns alternate over and under axial yarns. The mechanical interlocking and large unit cell size of the fabric architecture enable this material to behave like a structure. Many experimental results have demonstrated that triaxially braided composites can resist crack initiation and propagation as well as formation of large delamination between layers during impact loading [1]. However, characterization of this braided composite is complicated due to the nonuniformity of deformation within the unit cell as well as the possibility of the free-edge effect related to the large size of the unit cell when standard straight-sided coupon specimens are used [2].

Free-edge damage is typically initiated as a result of the differences in the Poisson's ratio of adjacent lamina [3]. This effect may cause failure of the material, beginning at the edges, with failure load values much lower than predicted. An impressive number of scientific studies on the free-edge effect is available, and a literature survey of this topic was presented by Mittelstedt and Becker [4]. As identified by Littell et al. [5] in six-layer straight-sided coupon specimen tests of a 0°/+60°/−60° triaxial braided composite, free-edge damage may cause significant reduction of transverse tensile strength and possibly a slight reduction in axial strength. To further investigate the free-edge effect, Kohlman [2] conducted axial and transverse tension tests using single-layer straight-sided coupon specimens, as single-layer specimens are useful in highlighting the local unbalanced lamination due to the absence of a suppressing effect from adjacent layers. It was identified that the edge effect could be caused by the unbalanced antisymmetrical layup of this triaxially braided composite [6]. It is also observed from tests conducted by Kohlman [2] and Littell et al. [5] that the measured properties are not quasi-isotropic, as both the modulus and strength in the transverse direction are lower than in the axial direction.

It was reported in our recent work [7] that the effective transverse modulus of the coupon specimen increases with increasing specimen width, which is very likely due to the presence of the free-edge effect. The purpose of this study is to find a potential way to provide accurate mechanical property data for large structures that are not likely to exhibit free-edge effect. In this paper, we

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investigate the impact of the free-edge effect on the effective elastic property of this braided composite. It was reported by Becker and Kress [8,9] that the effective coupon stiffness of laminated composites is reduced owing to the existing free-edge effect. However, there is little material available in the literature that discusses the influence of the free-edge effect on the effective modulus of triaxially braided composites. It was mentioned by D'Amato [10] that the number of tows within a specified width influences the extension modulus. Aoki et al. [11] claimed that the quasi-isotropy of initial modulus can be reached through a sufficiently large specimen size. Most recently, Kueh [12] investigated the size-influenced mechanical isotropy of triaxially braided composites and identified that the transverse behavior is sensitive to model size.

This research uses dimensional analysis to provide detailed identification and gain an understanding of the free-edge effect. This paper describes an experimental study aimed at elucidating the relationship of the free-edge effect to the effective elastic properties. Transverse tension coupon specimens with different widths were designed to contain a certain number of unit cells through the gage section, and digital image correlation (DIC) was used to monitor the specimens during testing. A previously developed meso-scale finite element model was applied to simulate the free-edge effect of a triaxially braided composite structure under tension and the mechanical responses of an infinitely large plate. The quantitative relationship of specimen size on the effective properties was then developed based on the numerical and experimental results. Further analysis was conducted to discover the inherent features of the free-edge effect in triaxially braided composites.

2. Material and test procedures

The material system we are studying in this work is a two-dimensional (2D) triaxially braided composite, a material having three distinct sets of yarns that are intertwined to form a single layer of 0°/±60° material. This single-layer specimen is studied (as opposed to a multilayer specimen) as it allows an increased ability to investigate the free-edge effect and its impact on elastic behavior, promotes a greater understanding of the failure mechanisms of this braided composite, facilitates conducting dimensional analysis experimentally (due to a much lower experimental loading capability being required) and simplifies the validation of the numerical model, which can then be applied to analyze multi-layer specimens. A typical 0°/±60° braided composite architecture is shown in Fig. 1(a). As can be noticed in this figure, bias fiber bundles undulate over and under each other alternatively, while the 0° yarns are straight and define the axial direction of the composite. The rectangle in Fig. 1(a) indicates the size of a unit cell, where the length is the axial distance between the center lines of two neighboring bias yarns and the width is twice the transverse distance between the center lines of two neighboring axial yarns. A unit cell is considered as the smallest repeating element that can represent the geometry and mechanical features of the composite.

The open source software TexGen (developed by The University of Nottingham and available at texgen.sourceforge.net) was applied to generate the meso-scale finite element mesh for a unit cell [13]. The braided geometry was first built by specifying the yarn path centerline (straight for axial fiber tows and a sinusoidal curve for bias fiber tows), defining the yarn cross section (ellipse) and the unit cell domain. The implemented Python script was then used to automatically transfer the geometry into finite elements. More details regarding the geometric modeling of textile composites can be found in the literature [14–16]. The meso-scale finite element mesh for a unit cell of this braided composite is shown in Fig. 1(b) (matrix elements are hidden), 1(c) and 1(d). There are 13,520 elements for the unit cell: 10 elements through the thickness, 26 elements in the axial direction and 52 elements along the transverse direction. In Fig. 1(b)–(d), the matrix elements are shown in gray, the axial fiber bundle elements are shown in dark blue, the +60° bias fiber bundle elements are shown in light blue, and the −60° bias fiber bundle elements are shown in green. The resultant fiber volume ratio is 86% in the axial fiber bundles and 69% in the bias fiber bundles. The unit cell can be divided into four subcells, which are labeled "A", "B", "C" and "D". Subcells A and C contain both axial and bias yarns. Subcells B and D contain only bias yarns. Subcell C has the same architecture as Subcell A, but it is flipped vertically. The inclusion of these subcells can be helpful in understanding the relationship of the free-edge effect to the details of the braided architecture, which will be presented in later sections.

The sample considered in the present study is a single-layer panel (a composite containing only one braided ply through the thickness) with a fiber volume ratio of 0.48. The composite is fabricated with 24 K T700s (Toray Carbon Fibers America, Inc.) axial tows and 12 K T700s bias tows impregnated by Epon E862 epoxy resin (obtained from Hexion Specialty Chemicals). The T700s carbon fiber is transversely isotropic with an axial modulus of 230 GPa and a transverse modulus of 15 GPa, while the epoxy resin is isotropic with modulus of 2.7 GPa as described in the manufacturer's technical data sheet and in Li et al. [17]. Single-layer composite panels with a ply thickness of 0.62 mm were processed using resin transfer molding and cured at 177 °C (350°F). In order to study the free-edge effect, transverse tension coupon specimens with a length of 279.4 mm (11 in.) and different widths were prepared for testing. The specimens were not cut based on specific values of width but according to the number of unit cells through the width as shown in Fig. 2. Specimens with 2, 4, 8 and 12 unit cells through the width are named TT2, TT4, TT8 and TT12, respectively. The four different types of specimens theoretically have the same geometry and should have the same effective properties without consideration of the edge effect. Also, using the number of unit cells as a measure of width can provide more accurate comparisons with numerical simulation results. To ensure that the specimens will fail at the gage section, 50.8 mm (2 in.) aluminum tabs are attached at each end of the samples, producing a 177.8 mm (7 in.) gage area.

Tensile testing was performed on an axial/torsion test machine capable of loading to 88.96 kN (20,000 lbs). All flat coupon tests were conducted under displacement control at a rate of 1.02 mm/min (0.04 in./min) in accordance with ASTM D3039 Section 11.3.2 for constant head-speed tests [18]. A digital image correlation (DIC) technique was chosen to measure full-field strain because it is able to provide full field strain and deformation measurements as well as information on the local surface. The DIC measurement system used in the testing program is commercially available and consisted of two stereo digital cameras connected to a computer with simultaneous image capture and DIC software. To obtain the full field deformation, a black-and-white speckle pattern was spray painted on the front surface (facing the cameras) of the specimens. During testing, a calibration process was first performed to calculate and store the relative camera position and orientation. Approximately 150 pictures were taken by the camera system, on average, during tensile loading. By tracking the locations of the pixel groups in real 3D space, the DIC software is able to compare the changing surface locations during loading with the baseline locations on an unloaded specimen (obtained from images taken immediately before the test) and calculates the relative and absolute displacements and strains. In order to generate stress–strain data, an approximately 18.5-mm-long (unit cell length in transverse direction) optical strain extensometer was created at