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The effect on elastic modulus of rigid-matrix tubular composite braid radius and braid angle change under tensile loading

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ABSTRACT

The objective of this paper is to assess changes in braid radius and braid angle of braided composite tubes under tensile loading using stereomicroscope digital image correlation (DIC) based optical measurement techniques. Using this approach, displacement fields were calculated and three dimensional surfaces were reconstructed. The radius of the tube and the braid angle were determined from the reconstructed surfaces and images. With this initial work showing the effects of tensile loading on the tube radius and braid angle also included development of approaches for deconstructing data. Results highlight that there is ∼10% difference between findings for elastic modulus between existing investigation techniques and the methods developed here for rigid-matrix composite braids.

1. Introduction

Braided composites are used in many industries and their use continues to grow [1] as a results of their capability of providing necessary strength and stiffness. The stiffness of a tubular composite braided structure is geometrically dependent on the radius and wall thickness in addition to its unit cell and material-based elastic modulus [2]. Studies have looked at the relations between wall thickness, braid angle, and braid radius because of their importance in characterizing composite braids as structural components [3,4]. Thus, knowing the radius and braid angle of a tubular braided composite is critical for stiffness critical applications and composite braid modeling.

A new technique, digital image correlation (DIC), is now being used for textile-based composites to characterize elastic properties and geometries. The technique measures surface deformation by comparing the relative gray scale intensities between a reference and deformed image [5]. The reference and deformed images are divided into evenly spaced subsets forming a grid. Each subset contains variations in gray scale, which are used to match the subset between a reference and deformed image. A correlation algorithm is applied within each subset to find the location of peak correlation between the reference and deformed image. The vector from the center of the subset to the location of peak correlation is the average displacement vector for the subset. The reference and deformed image are cross correlated to give a displacement vector field. The progression from 2D vector fields to the calculation of 3D vector fields requires two cameras. Surfaces are reconstructed by first identifying similar points between stereo image pairs. A stereo cross-correlation algorithm uses the identified points to find the corresponding points between the two images. Mapping functions, which were calculated during calibration, are then used to determine the x, y, and z coordinates of all points that can be used to describe the surface of the geometry. The mapping functions and the surface are then used to combine the two vector displacement fields from camera 1 and 2 to create a 3D vector field [6].

Studies that apply DIC to textile composites commonly focus on the onset and growth of damage. In some studies, DIC reconstructed surfaces were used as a visualization tool for damage progression of fiber composite pressure vessels [7]. Others have used 3D DIC to reconstruct and measure surfaces of cylinders [8,9], and a satellite dish [10]. These studies focused mainly on the ability to reconstruct an accurate surface using DIC. A further study, by Luo and Chen [11], measured the curved surface of a cylinder under axial loading. This expanded surface measurements to include deformation.

Many studies have looked at the effect of braid angle on elastic properties of composite braids, both experimentally [4,12–14] and theoretically [15–19]. A diamond braid preform architecture and a post cure composite braid are shown in Fig. 1. A sample-based coordinate system convention is also given in this figure with the x-axis positive to the right, y-axis positive to the top, and the z-axis is positive out of the page. The strength and stiffness of a composite braid can be largely influenced by braid angle [20]. Braids are cross ply composites, where the strand angles are mirrored about

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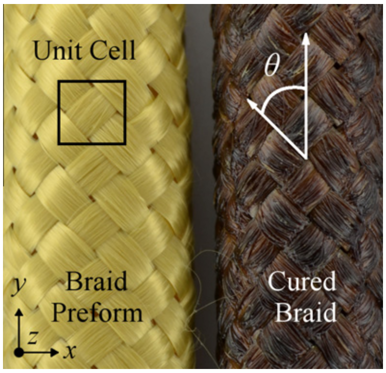

Fig. 1. A braided preform and cured braid with the coordinate system convention.

the central axial axis of the structure. The braid angle (θ) is defined as the angle of the strands relative to the axial direction of the braid. It is an important geometric factor that greatly affects the mechanical properties of composite braids [17].

Xu et al. [15] modeled biaxial and triaxial braids of differing textile architectures to predict the material properties with relation to the braid angle. Other studies looked into the effect of fiber architecture on the deformation and elastic moduli of braided composites both experimentally and analytically [1,12,14,16,20–22]. It was found that for tubular braided composites, as braid angle decreases the longitudinal elastic modulus increases. However, these studies assume that the braid angle remains constant during loading. Studies focusing on the change in braid angle during loading have not been found.

The length, radius and braid angle of a tubular braid preform are all dependent on one another [3,20]; when a braid preform is loaded in the axial direction the braid lengthens in the axial direction, decreasing the radius and braid angle of the braid. In an epoxy matrix composite braid similar behavior is expected from the reinforcing fibers; however, it has been assumed in the current literature that the rigid matrix prevents large scale deformations from occurring [17]. If the braid radius experiences changes, the cross sectional area of the sample will also change, altering stress calculations and affecting the accuracy of predictive models [12,21]. Contrary to all current methods, we propose to investigate the effect of using the instantaneous cross sectional area to calculate stress and elastic properties to provide more accurate experimental data for modeling.

This study aims to investigate the change in outer surface nominal radius, and unit cell braid angle of tubular composite braids. Loading on these tubes under progressively increasing tensile loading will be determined using 3D DIC to determine surface strain and surfaces reconstruction. It further aims to provide insight on the impact of radius and braid angle changes on experimental measurements and elastic moduli prediction models.

2. Experimental

2.1. Sample preparation

Tubular diamond braided composites were used in this study follow the procedures of previous work in our research group [21]. The braided sock preforms were produced using a braider (K80-72, Steeger USA, Inman, South Carolina, USA) configured to produce diamond braid patterns. Kevlar fibers (Kevlar 49, 5680 Denier, Dupont, Mississauga, Ontario, Canada) were used as the reinforcement material. The preform was placed over a smooth polytetrafluoroethylene (PTFE) mandrel with an outer diameter of 11.39 ± 0.03 mm. Fibers were manually impregnated with a thermoset epoxy consisting of an EPON Resin 825 (Resolution Performance Products, Pueblo, CO) and an Ancamine 482 hardener (Air Products and Chemicals, Allentown, PA) mixed at a 100:19 weight ratio. The braids were placed upright in an oven to ensure an even coating and allowed to cure for 2 h at 110 °C [21]. The cured braids were cut to length and bonded to end tabs using the same epoxy resin and curing process as the braid matrices to allow for tensile testing.

A total of 31 braided composite samples were manufactured with the following average standard deviation geometric characteristics: braid angles of 42.48° ± 1.96°, gauge lengths of 90.82 ± 1.54 mm, wall thicknesses of 1.02 ± 0.05 mm, and outer radii of 6.65 ± 0.06 mm. Gauge length and wall thickness measurements were made using a digital caliper (0–150 mm ± 10 μm, Mastercraft, Canadian Tire). Outer radii measurements were made three times on each braid sample using a micrometer (Outside Micrometer 0–25 mm ± 5 μm, Mitutoyo, Mississauga, Ontario, Canada). Initial braid angles were measured off a projected image of the braid surface using a protractor with one degree increments.

A randomized speckle pattern was applied to the surface of the braids to perform DIC based measurements as detailed in Leung et al. [9]. Braids were first painted with a flat black spray paint to reduce lighting reflections, and give a cleaner speckling surface. A fluorescent paint (Createx 5404, Createx Colors, East Granby CT) and reducer (Createx W100 Wicked, Createx Colors, East Granby CT) was used at a 2:1 ratio. The fluorescent speckle pattern was applied using the mixed paint and an airbrush (custom-B micron, Iwata-medea Inc, Portland OR), similarly to Berfield et al. [23]. To excite the fluorescent paint speckles, a 2.64″ ring light (Edmund Optics, Barrington, NJ, USA) with a 365 nm black-light (Edmund Optics, Barrington, NJ, USA) was used. An example image of the resulting speckle pattern is shown in Fig. 2. The image covers approximately 2 unit cells and braids as well as individual fibers can be discerned.

2.2. Experimental setup

For this study digital image correlation was used to measure surface deformation and reconstruct the surface of the composite braid samples. The testing equipment and its arrangement used for this study can be seen in Fig. 3. The two 1376 × 1040 pixel, 12 bit, charged-couple device (CCD) cameras (LaVision Imager Intense, LaVision GmbH, Gottingen, Germany) used for capturing images were attached to a stereomicroscope (Zeiss Stereo Discovery V8, Carl Zeiss MicroImaging GmbH, Gottingen, Germany). The stereomicroscope was mounted onto a rail extending from the

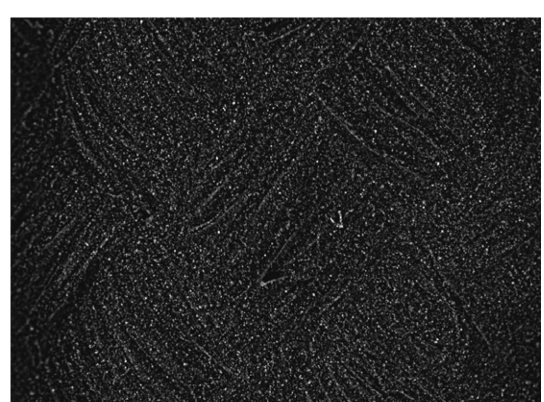

Fig. 2. Images of a sample surfaces with the applied fluorescent speckling pattern. White marks indicate the fluorescent particles applied to the braid surface. Braid fiber tows can also be seen.