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Predicting the longitudinal elastic modulus of braided tubular composites using a curved unit-cell geometry

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ABSTRACT

Predicting the elastic constants of braided composites has gained increasing importance over the years. This is mostly due to the broad use of the braided composites and the need to accurately predict their response during stiffness critical applications. This paper outlines an analytical study to predict longitudinal elastic modulus of two-dimensionally braided composites. The developed model analyzes a small repeating representative block, a unit cell, of the braided structure. Unlike most of the previous studies in the field, the model recognizes the effects of curvature of the unit cell on tubular braided composites as a function of braided tube diameter. This paper outlines the development of the proposed analytical model, as well as validation of the model for stiffness critical applications by comparison of the results with available literature data and experimental findings.

1. Introduction

Braiding has been used for years to produce textile fabrics [1]. Increasing demand to produce fast, better, and automated composite material preforms forced researchers and engineers to utilize braiding as one of the techniques that fulfills this requirement. Braiding is one of the top choices of composite manufacturers for many applications due to the advantages it offers; such as increased toughness, control over fiber deposition angle and fast fiber deposition rate. Some of these applications can be listed as braided air ducts, aircraft structural parts, automotive shafts, braided catheters, braided stents and braided composite dental posts [1–5].

Optimal use of braided composites is possible via use of accurate models to predict their mechanical properties. Over the years, researchers developed both numerical and analytical models. Although accurate, numerical models are found to be rather lengthy due to the complex geometry requirements for stiffness calculations [6]. Analytical models, on the other hand, can provide sufficiently accurate data with less processing time and computer power requirements [5].

Many of the analytical models developed for woven-fabric and braided composites utilize Ishikawa and Chou's work developed for woven fabrics [7]. Authors proposed mosaic, fiber undulation, and bridging models that utilize the well-known Classical Laminate Plate Theory (CLPT) as a base for the calculations. The fiber undulation model was extensively modified and used by the braiding community as this model accounts for the undulation of the fibers between the cross-over regions of a braided structure for more accurate results.

Redman and Douglas predicted the tensile elastic properties of braided composites using a combination of rule of mixtures and Classical Laminate Plate Theory (CLPT) [8]. The authors neglected the undulating strand in their study by assuming the length between two neighboring strands to be large.

Soebroto et al. used Fabric Geometry Model (FGM) to predict the engineering properties of braids [9]. FGM uses a simplified geometry of the reinforcing elements and volumetrically combines the stiffness of these elements [9]. This model treats the reinforcement as a linear element hence may be seen as omitting the effect of undulation in the predictions.

Falzon et al. investigated a number of models to predict the stiffness of woven composites [6]. The authors divided the models into three main categories, namely, elementary models that rely on a generalized Hook's law, CLPT models, and numerical models (i.e. finite element models). The authors concluded that elementary models were simple but not suited for strength analysis, laminate theory models were limited to in-plane property predictions and not suitable for complicated architectures, and finite element models were suited for strength analysis but required detailed geometrical details [6].

Since, many new models have been published in the literature, and with the use of advanced computing capabilities both numerical and analytical models have developed to account for the limitations of the earlier models and to predict elastic properties of

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braided composites [10–16]. A detailed investigation of these works, along with others, has been published [5].

Many of these models were developed for flat-braided structures and predicted the properties through a flat-unit cell, or neglected the effects of curvature in tubular braids such as in works of Aggarwal et al. and Carey et al. [12,16]. This assumption may be acceptable for tubular structures with relatively large radii; however, it maybe not be for braided structures with smaller radii, such as braided catheters and stents.

Medical use of braided composites is rapidly increasing. The delicate use of braided tubular medical tubes in the human body requires thorough understanding of their mechanical properties. Hence, accurate models that predict composite material elastic properties must be developed and verified experimentally.

Carey et al. modified Raju and Wang's predictive model, developed for woven composites based on a generalized CLPT analysis, to predict elastic properties of diamond braided composites [16,17]. Unlike some of the available simplified models, Carey et al.'s model included the possible effect of open-mesh regions (i.e. matrix-only regions due to extensive undulating regions); however, the model neglected the effects of the curvature on the unit cell and assumed a flat-unit cell even for tubular braided composites.

Potluri et al. [18] and Potluri and Manan [19] investigated the thicknesses of braided tows. The authors calculated the thickness of the tows to find the softened tow properties for use in a Modified Lamination Theory based model, which was also used by Byun in flat braided triaxial composites [10]. The authors suggested the thicknesses should be individually investigated. Authors did not include the open-mesh regions, although their unit cell indicates these regions, and did not study the effect of tube radius on the properties.

The proposed model is based on Carey et al.'s model; however, it is developed to evaluate and recognize the effects of the curvature on the elastic properties of the unit cell as a function of the tubular braided composite's diameter.

2. Proposed model

An initial version of the model was presented earlier [20]. Here, the detailed derivation, comparison of results with other available models and experimental results presented in the literature, and in-house experimental results are presented to validate the model.

In two-dimensional tubular braided composites, fibers are deposited on a cylindrical mandrel and impregnated by a matrix material. In this process, the diameter of the mandrel gains importance since each unit cell and the fiber-tow geometry in the unit cell would have a more pronounced effect depending on the diameter of the mandrel, i.e. curvature of the unit cell.

Fig. 1 presents the top-view an isolated unit cell. The unit cell is composed of three different regions, namely: crossover (where fiber tows lay on top of each other), undulating, and matrix-only regions. The strand thicknesses in the crossover regions of large-diameter tubular braids can be assumed almost identical as the radius of curvature of the unit cell can be assumed infinite; hence, the elastic properties of such structures can be predicted using flat-unit-cell geometry.

In reality, the unit cell of a tubular braided structure has a curved geometry, (Fig. 2), and the radius of curvature of the unit cell is a function of the tubular diameter. As the diameter of the tubular braid decreases, the thicknesses of the strands deposited on the mandrel become un-even, (Fig. 3). The change in the curvature of the unit cell and the un-even strand thickness must be accounted for through geometrical characterization of the unit cell to obtain more accurate elastic property predictions.

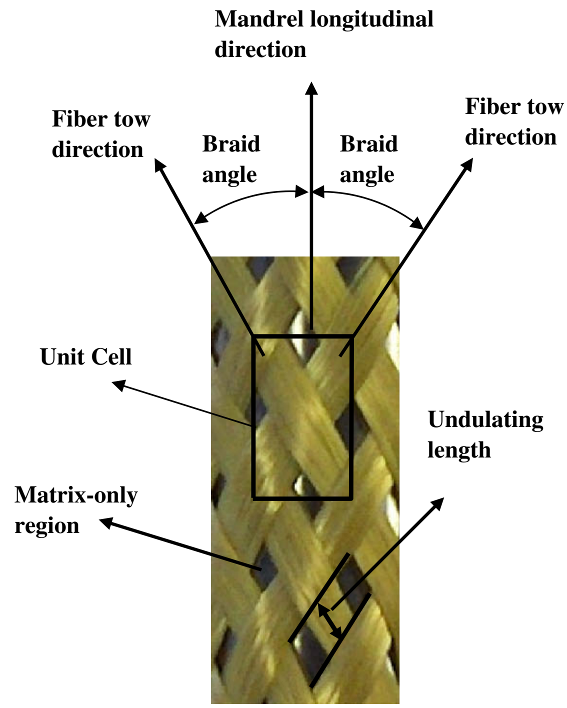

Fig. 1. Top view of a unit cell.

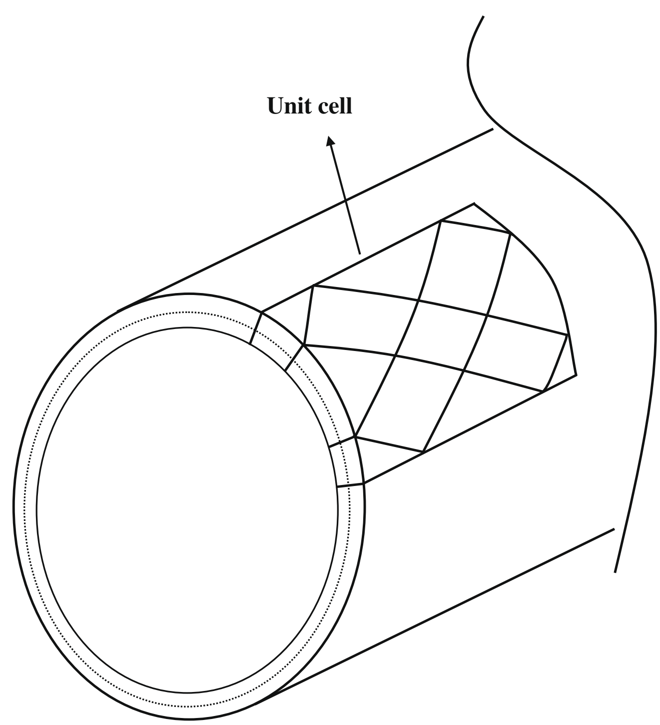

Fig. 2. Schematic representation of a curved-unit cell on a tubular braided composite.

2.1. Geometric characterization

Schematic representation of a curved-unit cell is shown in Fig. 4. The unit cell is characterized with respect to the radius (r) of the unit cell (i.e. radius of the tubular braided structure), the arc angle (φ_c) covered by the unit cell, and the longitudinal direction (y) of the unit cell/tubular braided structure. The braid angle