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Design and manufacturing of an L-shaped thermoplastic composite beam by braid-trusion

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ABSTRACT

Braid-trusion is a manufacturing process for composite materials in which a braiding machine is coupled with a pultrusion die to continuously produce beams with constant cross-section and off-axis fiber orientation. This study presents a geometrical model of the tri-axial braid which allows the design of braided preforms that achieve correct filling of the pultrusion die at the same time as it limits fiber friction on die walls. The typic design parameters are listed and used for the manufacturing of a braid-truded thermoplastic composite beam where fibers are aligned at ±69° as well as 0° with respect to the beam axis. Tensile mechanical characterization and cross-section observations are also presented.

1. Introduction

Braiding is a traditional textile technique that has found several new industrial applications. High modulus fibers, such as carbon fibers, can be braided and consolidated with a polymer matrix to form structural members that possess outstanding mechanical properties. Braided composites have received great attention from the automotive industry for its enormous potential as energy absorption members in crushing situations [1].

However, to achieve successful implementation of braided structures in the automotive industry, several challenges must be overcome without sacrificing the product performance. The most important one is achieving high production rate. Another challenge with increasing importance is the production of environmentally friendly primary structures. Thermoplastic composite pultrusion is a continuous manufacturing process that produces constant cross-section beams of structural quality using recyclable matrices [2]. Inorganic fiber reinforcement (e.g., glass fiber, carbon fibers) is pulled through a heated die jointly with a thermoplastic polymer matrix. The heated die has a taper region where the molten polymer impregnates the fiber bed. There is also a constant cross-section region that gradually cools the matrix and forms the beam at its constant cross-section dimensions. The operating parameters, i.e. the pull speed and the die temperature, have to be adjusted to a given die geometry so that the composite is properly consolidated at die exit [3].

The fibers are usually oriented parallel to the direction of the pultrusion. Few processes exist to control the fiber orientation of pultruded products. Some early works reported the pultrusion of braided fabrics, hence, giving a possibility of introducing oriented fibers with respect to the beam axis in this continuous process [4,5]. The "braid-trusion" combines a braiding machine as the material feeding system with the pultrusion die system. However, recent investigations have demonstrated that the braided preform must be carefully designed to be able to control the fiber orientation in the braid-truded beam [6].

Several models have been developed to describe the braid geometry. Brunnschweiler adapted Pierce's theory for woven fabrics to braided fabrics in the 1950s with the objective of estimating the crimp path of braided yarns and the locked configurations [7–9]. The "Handbook of Industrial Braiding", published in 1989, also provides good indication of the important parameters of braided fabrics using simple equations [10]. Pastor et al. developed a modeling procedure of textile reinforcements using the Bezier curve and the Lagrange's principle of minimum work [11]. Robitaille et al. developed a formal procedure to represent the interlacing path of yarns in braided fabrics based on a series of vectors in the fabric unit cell [12]. Other studies presented a computer program and an experimental verification for modeling the braided fabric meso-structure [13,14]. These models provide good approximation of the braided fabric structure but are often mathematically complex or hidden behind proprietary code. Moreover, the braid structure is always represented by a flat unit cell, which does

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not represent the circular nature of tubular braids. Also, these models do not evaluate the deformation of the braided fabric when it is pulled through a pultrusion die. Hence, there is a need to develop a simple geometrical braid model that can be readily adaptable to braid-trusion.

This study presents a geometrical model for tri-axial tubular braids. This model is then used to describe the phenomena occurring in the braid-trusion manufacturing process. Using this theoretical description, a design procedure is proposed for the successful design of braided fabric for the braid-trusion manufacturing process. Finally, an experimental braid-trusion is performed using the suggested design procedure.

1.1. The braid model

The three-axial tubular braided fabric possesses yarns continuously spiraling along the braid axis, called the braiding yarns (BYs). The BYs are divided into two sets intertwined in opposite directions along the braid axis. Another set of yarns, called the middle-end-yarns (MEYs), is laid inside the braid along the axis direction and is locked-in by the two sets of BYs. The MEYs are introduced for dimensional stability, and longitudinal mechanical properties improvement [10]. Finally, a third set of yarns, called the core yarns (CYs) can be placed inside the braid along the braid axis. All the yarns are assumed to have an elliptic cross-section characterized by a given width and thickness (a_Y, b_Y). In the regular braided fabric, each BY continuously passes under two other yarns and then over two yarns of the opposing set. Fig. 1 shows the braided architecture and a representation of the BY path.

The pitch length (p) is the distance for one BY to execute a complete rotation around the braid axis (see Fig. 1a). Fig. 2 introduces the several types of braid diameters that can be defined. The internal diameter (D_{in}) is also equal to the mandrel diameter when the braid is formed onto a cylindrical support. The diameter of internal BYs ($D_{BY,in}$) is the diameter of the circle passing at the middle of the innermost BYs. The braid diameter (D_{Braid}) is the diameter of the circle passing through all the MEY centers. The diameter of outside BYs ($D_{BY,out}$) is the diameter of the circle passing through the outermost BYs' centers. Finally, the outside diameter (D_{out}) is the diameter of the virtual cylinder enclosing the braid on its external surface. Defining different braid diameters leads to the definition of different fiber angles depending on which diameter the fiber is positioned. Eq. (1) shows three different fiber angles: the internal BY fiber angle (θ_{in}), the average braid angle (θ_{Braid}), and the outside BY fiber angle (θ_{out}), which are all calculated with the same braid pitch value.

$$\theta_{in} = \arctan\left(\frac{\pi D_{by,in}}{p}\right) < \theta_{Braid} = \arctan\left(\frac{\pi D_{Braid}}{p}\right) < \theta_{out} = \arctan\left(\frac{\pi D_{By,out}}{p}\right) \quad (1)$$

The braiding machine controls the braid pitch. The pitch distance is determined by the ratio of the pulling speed of the braid structure over the rotation speed of the BY carriers around the braider head [15]. The braid diameter can be controlled using a forming mandrel. If no mandrel is used, the braid diameter will reduce until the braid reaches a "locked-state", often referred to as the tensile jammed position [8]. At this locked-state, the contact between compressed BYs and MEYs prevent the further reduction of the braid diameter when the preform is subjected to a pulling force on the axial direction.

Fig. 1b shows the BY path in one braid repeat length. The BY path is assumed here to be constituted of a cosine that can be expressed using Eq. (2), where the value N_{BY} is the total amount of BYs.

$$y = \frac{(b_{By} + b_{MEY})}{2}\cos\left(\frac{\pi N_{BY}\cos\theta}{2}\right), \quad \text{with } 0 \leqslant x \leqslant \frac{2p}{N_{BY}\cos\theta} \quad (2)$$

The maximum crimp angle α is calculated at half of the plait length from the derivative of the BY cosine path, as shown by Eq. (3).

$$\alpha = \arctan\left(\frac{N_{BY}}{4p}(b_{BY} + b_{MEY})\pi\cos\theta\right) \quad (3)$$

The length of the cosine braiding yarn centerline of Eq. (2) can be calculated using numerical integration (see Appendix A). The crimp ratio of the BY can be calculated for one repeating unit of the cosine curve according to Eq. (4). The length of the cosine braiding yarn path (L_{BY}) is divided by the spiral length of the braiding yarn projected onto the average braid diameter cylinder.

$$R_c = \frac{L_{BY}\cos\theta}{p} \quad (4)$$

The unconsolidated yarn cross-section area (A_Y) refers to the yarn material area (S_Y) by a yarn fiber packing ratio (R_P) according to Eq. (5). The yarn fiber packing is assumed here to be between 0.5

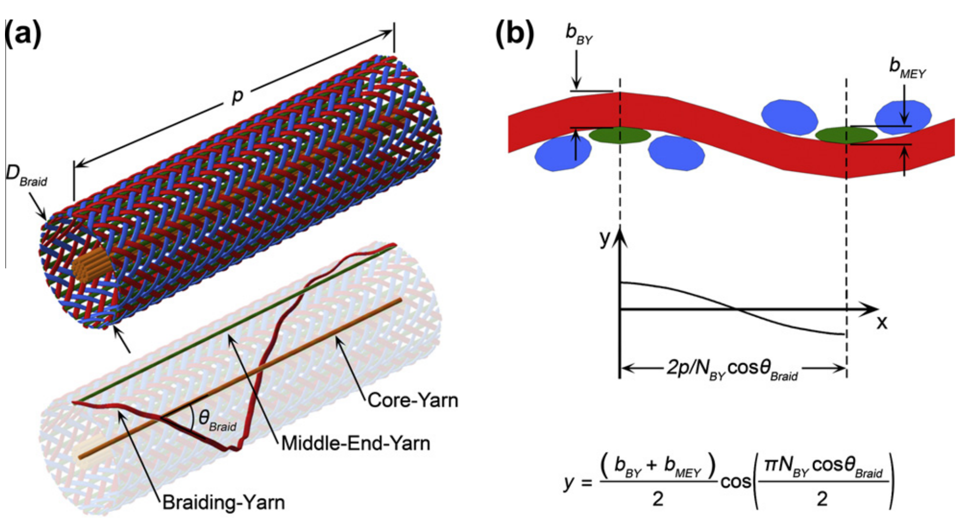

Fig. 1. Braid architecture: (a) localization of the braiding yarn, middle-end yarn and core yarn for one pitch length and (b) the fiber path is represented by a cosine. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)