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Investigation into the changes in bending stiffness of a textile reinforced composite due to in-plane fabric shear: Part 2 – Numerical analysis

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ABSTRACT

Numerical investigations were pursued in an effort to understand the relationship between changes in the stiffness of plain-weave fabric-reinforced plates and the degree of in-plane shear within the fabric reinforcement. These numerical studies were motivated by an experimental study where the measurable geometric changes discerned among plates with different levels of in-plane shear were (1) the reorientation of the fibers within the plane of the plate, (2) an increase in thickness with increasing in-plane shear, and (3) the change in width of the fiber tows as function of in-plane shear. Finite element models were used to investigate the individual contributions of these geometric changes on the bending stiffness of the plates. For the material system considered in this study, the reorientation of the fibers and the change in plate thickness as a function of the state of shear were concluded to be the dominant factors affecting the bending stiffness of the plates. The change in cross-section orientation about the tow axis was determined to be insignificant.

1. Introduction

Fiber-reinforced composites are becoming popular materials across a wide spectrum of industries [1–4] due to their high specific-strength and specific-stiffness characteristics [5–7]. Textile-reinforced composites are particularly attractive for their potential to save time during the manufacture of composite structures. Automated manufacturing techniques, such as thermoforming, compression molding, and hydroforming, have the ability to transform a two-dimensional textile into a three-dimensional structure within one manufacturing step [8–10].

As the fabric conforms to complex three-dimensional molds, there are three major modes of deformation occurring within the textile: the tows can stretch, the fabric can shear, and the tows can bend in-plane and out-of-plane. Many researchers have devoted time and effort to understand this shear deformation during the forming of composite structures [11–20]. The current paper will solely examine shear dominated phenomena. When the fabric shears, the tows that were originally mutually perpendicular rotate within the plane of the fabric, thereby resulting in non-orthogonal fiber orientations. An example of this deformation is illustrated by a hemisphere formed from a plain-weave fabric as depicted in Fig. 1. Many researchers have presented finite element models that consider the mechanical behavior of the textile during the manufacture of a composite structure to predict the final orientations of the fiber tows [21–37]. These simulations aid in the design of molds used to form the material and to assist in the selection of fabrics to satisfy the drapability requirements of the part geometry. However, little research exists in the open literature linking the results of these forming models to the structural behavior of the composite part.

The current research is part of an introductory study directed at developing a fundamental understanding of the effect of sheared fabric-reinforcements on the stiffness of composite plates, which is presented as a two-part series. Such a study is the first step necessary to link the results of the robust forming models presented in the literature to the mechanical properties of the composite. In Part 1, the effects of in-plane shear on the flexural behavior of textile-reinforced composite plates were examined using an experimental approach, and the manufacture of the plates with various degrees of in-plane shear within the textile reinforcement was discussed in detail [38]. In Part 2, the respective significances of the geometric changes within the plates caused by the shearing of the fabric reinforcements are investigated using a numerical approach. These geometric changes include (1) the reorientation of the fibers within the plane of the plate, (2) an increase in thickness with increasing in-plane shear, and (3) the change in width of the fiber tow as a function of in-plane shear. The numerical approach allows for examining the significance of the contribution made by each of

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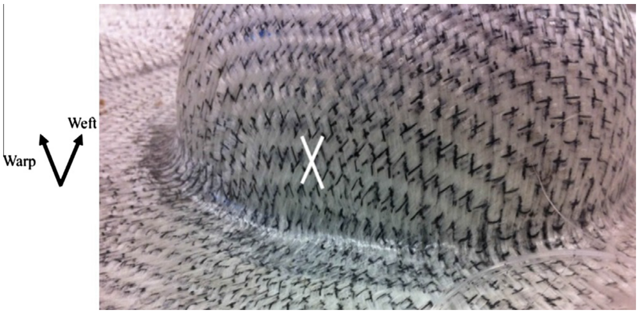

Fig. 1. Shear deformation of a woven fabric formed into a hemisphere. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the three geometric changes to the effective bending stiffness of each plate. The current study will provide a fundamental understanding of what geometric attributes must be captured by the manufacturing simulation to use the results to calculate the mechanical behavior of the composite. Additionally, the current work will demonstrate what attributes are necessary in a robust composite material model that accurately depicts the behavior of textile-reinforced composites. The results of this study will allow researchers to connect the structural composite model back to the forming simulation, thereby linking the stiffness of the final consolidated part back to the manufacturing processing conditions.

2. Critical investigation of the factors influencing flexural stiffness of sheared plates

Part 1 of this investigation [38] described the manufacture of composite plates reinforced by textiles with various degrees of in-plane shear. The current work will refer to two coordinate systems defined by the plates' geometries, as depicted in Fig. 2. The global *XY* coordinate system remains parallel to the edges of the composite plate. In plates reinforced by undeformed textiles, the *X*-axis is parallel to the weft tows and the *Y*-axis is parallel to the warp tows. The global *XY* axis is independent of the degree of shear in the textile reinforcement and the axes remains perpetually orthogonal. The local *xy* coordinate system follows the orientations of the tows within the plate and is dependent on the shear angle, γ, in the fabric reinforcement. The local *x*-axis remains parallel with the weft tows and the local *y*-axis remains parallel with the warp fibers. The plates considered in the current work were cut such that the weft fibers remained parallel with the edge of the plates, i.e. the global *X*-axis and local *x*-axis remained parallel.

The load–displacement curves for flexure tests performed in Part 1 of the analysis [38] are depicted in Fig. 3(a) and (b). The respective slopes of the load–displacement curves, shown in Fig. 3 (c) and (d), are directly proportional to the stiffness of the plate in each global direction. The increase in stiffness in the *X*-direction as the shear angle within the reinforcement increased was expected. However, the plates that were bent in the *Y*-direction did not follow the expected trend, i.e. a drop in stiffness as the warp tows rotated toward the weft tows. In an effort to understand this phenomenon, a critical investigation of the potential factors leading to this contradiction was pursued in the current study. Additionally, geometric changes in the textile-reinforcement were observed as a function of in-plane shear. Most notably, the thickness of the plate increased as the fabric shear angle increased, and the width of the fiber tows decreased as the shear angle increased.

The current investigation began by considering Classical Laminate Theory (CLT) to explore the mechanics of an anisotropic plate in flexure. This application of CLT lead to exploring how the geometric changes observed as a function of textile shear contributed to the effective flexural stiffness.

2.1. Application of classical laminate theory

CLT relates applied loads on a laminate to the associated stresses, strains, and deflections of the composite structure [6]. The application of CLT is generally limited to composites reinforced by layers of unidirectional fibers with a constant fiber volume fraction. Composites reinforced by textile-reinforced composites are difficult to analyze due to the internal geometry of the reinforcements. However, some relations can be used to analyze the global behavior of the composite. The laminate's global stiffness matrix, commonly referred to as the ABD matrix, relates the strains experienced by the geometric midplane of the composite to the applied loads through the following relations in the global coordinate system defined in Fig. 2:

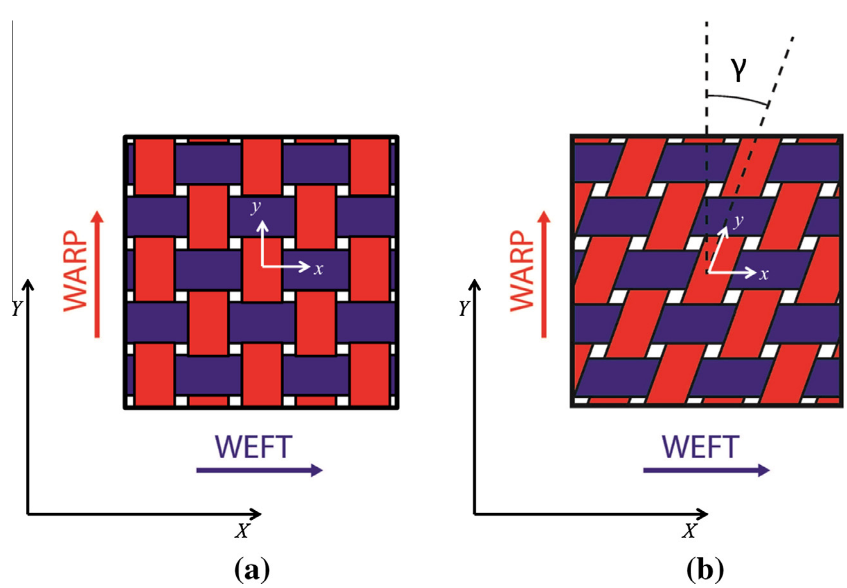

Fig. 2. Local *xy* and global *XY* coordinate systems depicted for (a) undeformed textiles and (b) textiles with a shear deformation equal to γ. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)