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Size-influenced mechanical isotropy of singly-plied triaxially woven fabric composites

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ABSTRACT

Mechanical isotropy of triaxially woven fabric composite is investigated analytically, numerically using beam lattice models, and experimentally under tension and bending loads, due to evidence suggesting that its commonly regarded quasi-isotropy is shattered by size effects. Models verification has found that the sawtooth configuration best fits the observation. Employing therefore this configuration and varying model size, it is remarked that the mechanical behaviors are sensitive when loads are perpendicular to the tows direction while no obvious perturbation is seen when loads align with the tows. For practical convenience, time-saving universal equations that are mechanically meaningful are formulated, catering both loading directions for both pre- and post-straightening states for arbitrary size.

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1. Introduction

Triaxially woven fabric (TWF) composite is commonly regarded as one of the materials that diminishes anisotropy, a well established behavior of fibrously reinforced solids. It offers attractive quasi-isotropic properties due to its equal arrangement of reinforcements on a planar manner. A particular type of single ply TWF, as shown in Fig. 1, consists of a set of fill yarns, oriented at the 0°-direction (horizontal in the figure), and two sets of warp yarns, arranged at angles of ±60°. Beneficial structural properties of this textile composite include high performance in terms of stiffness, strength, good tearing and bursting resistances, relatively lightweight, and elastically flexible, attributing to an observably quasi-isotropic macroscopic behavior in the company of hexagonal holes spread over the composite, the features of which are strongly fascinating for low mass foldable structures. Since these characteristics are achievable using solely one ply of TWF, related issues derived from the delamination as typically seen in the laminated composites are not particularly of concern. Also, this textile composite shows better shear resistance without offsetting from its single ply feature when compared with those of biaxially woven fabric (BWF) composite varieties.

A cautionary mode must however be exercised in the use of this material due to findings documented in several papers, giving the impression that this material is remote from predictable state [1,2]. The key issues can be identified as follows. Firstly, TWF structure gives, owing to its unique woven nature, more subtle responses than typical plied and flat composite materials. Secondly, the uniform distribution of hexagonal holes distinguishes not only in terms of its physical appearance, but also the way that its mechanical responses can be predicted, especially when compared with conventional biaxial textile composites. Also, size effects arise when one of the dimensions is to a certain extent reasonably greater, the subject of which will be further explored in this paper.

In terms of generalizing the mechanical properties of TWF with respect to aforementioned concerns, a better theoretical justification is needed and is as yet unaccounted for. To facilitate our discussion, it should be noted as shown in Fig. 1 the orientations of 0°- and 90°-directions. The 0°-direction loading designates the load prescription along the tow direction whereas the 90°-direction loading describes that perpendicular to the tow. If we look at the planar presentation of TWF as depicted in Fig. 1, a direct approach to make prediction of its material behavior without having a close inspection is by assuming it as a laminate consisting a [0/60/−60] stacking sequence or any permutation of ply arrangement using these angles. It is however obvious that the only way such a sequence can produce a quasi-isotropic relationship is through the abiding of $\left[0/\frac{\pi}{n}/\frac{2\pi}{n}/\cdots/\frac{(n-1)\pi}{n}\right]_s$ or $\left[\frac{\pi}{n}/\frac{2\pi}{n}/\cdots/\pi\right]_s$ configuration where n is one half of the total layer number of laminate and s denotes for symmetry. Through woven structure of TWF, this symmetry is achieved since there exists an equal amount of 0° and ±60° components about the mid-plane of the material. This is a general, commonly conceived view of researchers working on TWF. Theoretically speaking, such interpretation has a solid standing. But, the applicability of this concept vanishes when the size

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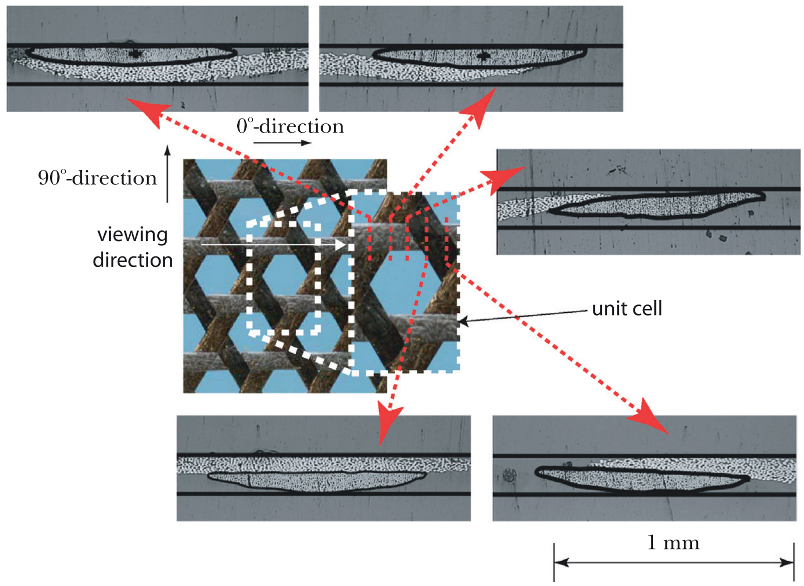

Fig. 1. A piece of triaxially woven fabric composite and its unit cell as well as a set of micrographs showing the cross sections, sliced with intervals of about 0.5 mm, along a tow direction. Scale is applicable for the cross sections only. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

variation of textile is considered, due to the occurrence of what the present paper describes as the quasi-isotropy shattering. This particular concern will be addressed in detail in this paper. Consequently, universal equations are offered to characterize the size and directionally affected mechanical properties arisen from this condition, incorporating the size effects as constituents, for practical convenience.

Now, we note that thus far there exist a number of works reporting on modeling techniques used to investigate the elastic thermo-mechanical behaviors of TWF. The issue of anisotropy of TWF has been pointed out in several papers, looking in particular the initial tensile moduli, employing customary sample size as suggested in various composite materials testing standards. In regard to a fixed TWF size, a comparative experimental study of the extensional properties of BWF and TWF was conducted by Fujita et al. [3] in the presence of multi-oriented tensile loads. They found that the strength of TWF is not isotropic even though its initial stiffness is in close proximity to isotropic condition. In-plane shear was reported to be better resisted by TWF compared with BWF due to the lacking of reinforcement in the bias directions in the latter. An independent investigation carried out by Dano et al. [4], employing a specific size for all specimens, reported a 39% difference in initial stiffness when TWFs were independently loaded longitudinally and transversely. In addition, an anisotropy of 22% in Poisson's ratio was observed in the same study for these two cases. The weave was found to be axially stiffer and transversely less contractive when pulled in the direction of the tows. Finite element (FE) modeling issue had been explored by Mishra [5] using the solid element description for in-plane properties of TWF, focusing merely on the unit cell.

Via numerous numerical approaches, the aspect ratio effect had been studied by several researchers in terms of initial mechanical properties. In particular, D'Amato [6] argued that under the tows direction stretching environment, the number of tows within a specified width influences the extensional modulus. The ±60° tows contribute differently in accordance with the model size. On different account, Aoki et al. [7] pointed out that the numerical convergence to quasi-isotropy of initial modulus can be reached through a sufficiently large specimen size, using the inverse of material width as measure. Nevertheless, due to greater effect of free edges, both Aoki et al. [7] and Zhao et al. [2] remarked that the influence of the aspect ratio on the elastic constants of TWF are specifically more dominant in the 90°-direction stretching. Recently, Kueh [8] formulated a fitting-free hyperelastic strain energy function for TWF to describe its directionally guided non-linear behaviors when stretched in a planar manner in the 0°- and 90°-directions.

In this paper, we carry on the exploration of the mechanical properties of TWF in particular those of tensile and bending under the influence of variation in textile size, adopting analytical, numerical, and experimental approaches, the last method of which is used as the verification means. We will show in the end using a set of beam lattice models, though slightly anisotropic due to quasi-isotropy shattering in presence of size and edge effects, TWF mechanical properties can be forecasted by astoundingly simple equations. It is worthwhile to justify that the size effects on the Poisson's ratio and bending modulus of TWF have not been previously examined. Also, equations that generalize these effects have never been attempted before the current study. The paper is arranged as follows. The remainder of the paper initiates with the description of currently investigated material, in Section 2. It is followed by the investigation on its tensile and bending properties, in Sections 3 and 4, respectively. In Section 5, the size effects are explored, from which a set of mathematical functions to generalize TWF mechanical properties is formulated for practical convenience. The paper ends with a note on major findings.

2. Material description

For the material, the 'basic weave' TWF (Sakase Adtech, Japan), consisting of 1000-filament T300 carbon fibers (Toray Industries Inc., Japan) and the resin system Hexcel 913 (Hexcel, UK), was used. The composite has a dry areal mass of 75 kg/m^2 and an average thickness of 0.156 mm. Before curing, the vacuum bagging method was adopted in which TWF composite was sandwiched between two layers of resin film. In allowing for matrix melting, the resin films were preheated and thus infusing the dry fibers by means of capillary action. The mixed product was then cured in the autoclave at 120 °C for 2 h.

A series of micrographs showing the sections taken at intervals of about 0.5 mm along a tow direction, the viewing direction of which is guided with an arrow, is shown in Fig. 1. In general, the cross sections of tow are of imperfectly lenticular shape, with a

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