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MODELING TECHNIQUES FOR PREDICTING THE MECHANICAL PROPERTIES OF WOVEN-FABRIC TEXTILE COMPOSITES: A REVIEW

A. Dixit[1] and Harlal Singh Mali[2*]

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The paper reviews the past and recent modeling techniques (both analytical and numerical) pertaining to the mechanical behavior of textile-reinforced composites in general and woven fabric textile composites in particular published in the literature. The finite-element analysis of repeating unit cell geometry in association with the homogenization technique proves to be vital in predicting the properties. The purpose of this paper is not only to discuss the different modeling strategies and the mathematics involved, but also to provide the reader with an overview of the investigations conducted.

1. Introduction

Composite sections are generally used where there is a requirement for a high strength/stiffness to weight ratio, because their properties can be tailored to specific structural requirements. The anisotropy of composites offers a significant enhancement in their performance over conventional materials. Traditionally, fiber-reinforced composites formed from several layers of unidirectional (UD) tapes preimpregnated with a matrix material are used due to their excellent mechanical properties, such as high specific stiffness and high strength. However, laminated composite plates, which offer good in-plane properties, are prone to delamination due to their poor mechanical properties in the thickness direction. In an attempt to overcome this drawback, woven-fabric (WF) composites, also termed textile composites, are put to use, as they offer a 3D reinforcement in a single layer and provide better mechanical properties in both in-plane and transverse directions. Textile composites find application in many branches of industry thanks to their balanced mechanical properties [1], easy handling, and impact resistance [2].

[1]School of Engineering, Department of Mechanical Engineering, Gautam Buddha University, Greater Noida, India, 201310
[2]Mechanical Engineering Department, Malaviya National Institute of Technology, Jaipur, Rajasthan, India, 302017
[*]Corresponding author; tel.: +91-8829046492; e-mail: harlal.singh@gmail.com

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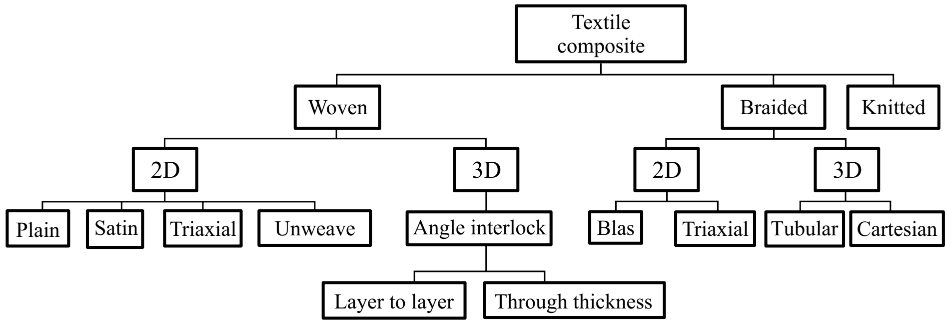

Fig. 1. Classification of textile composites.

The prediction of elastic properties of textile composites has been an active area of research in the past two decades, because the issues related to such parameters as fiber architecture, matrix properties, and fiber properties [3], affecting the mechanical characteristics of the composites, are highly complex. These factors make the modeling aspect of textile composites extremely challenging. Various assumptions were made by many researchers in the past to cope with the task. The rule of mixture, composite cylinder models, and boundary variation methods [4] are various techniques which provide approximate estimates for the mechanical properties of the composites, but they are limited to a simple geometry and cannot be applied to complex fiber architectures. Therefore, new analytical models are needed to effectively predict the mechanical behavior of textile composites and numerical techniques, such as the FEM, are also required to verify the validity of the models. The aim of this paper is to review the existing modeling methods for predicting the fundamental mechanical properties of woven composites and to provide the understanding of suitability of various analytical models and their experimental verification. Prior to this, a brief review of the manufacturing methods and architectural patterns of textile composites is presented in the next section.

1.1. Textile composites

The internal structure of textile composites has several scales. The strength and stiffness of the composites depend upon the polymer matrix and fibers at the molecular scale. A textile composite generally consists of a reinforcement material (carbon, glass, etc.) in a UD or fabric form, which is impregnated with a resin matrix at a predetermined and controlled level. This procedure is performed by using various liquid molding techniques, such as resin transfer molding (RTM), injection molding, and so on. There are usually four important levels in the manufacturing process of textile composites:

Fiber > Yarn > Fabric > Composite.

Generally, all 2D and many 3D textile composites can be considered as laminates, although their manufacturing methods differ from those for preparing the conventional tape lay-ups. The textile composites which in most ways behave like laminates fall into the category of quasi-laminar textiles, while those in which triaxial stresses exist and an optimum reinforcement plays a significant role are known as “nonlaminar” composites. An applicability-based classification of textile composites, with their strengths and weaknesses analized, was presented by Pastore [5]. Depending upon their formation techniques, textile composites can be separated into three categories [6] — woven-, knitted-, and braided-fabric ones, as shown in Fig. 1.

1.1.1. Woven fabric. Woven fabric is one of the most widely used materials in structural applications [7]. They are produced by weaving a continuous fiber, also called the reinforcement, by using multiple weaving methods and then impregnating the weave with a second material, called matrix, to form a composite. The weaves generally consist of two sets of interlaced fiber bundles, named yarns or tows. The yarns/tows which run horizontally or lengthwise are termed the warp, but the vertical bundles are referred to as the fill [8]. The pattern in which the warp and weft bundles are interlaced is termed the weave [9]. A

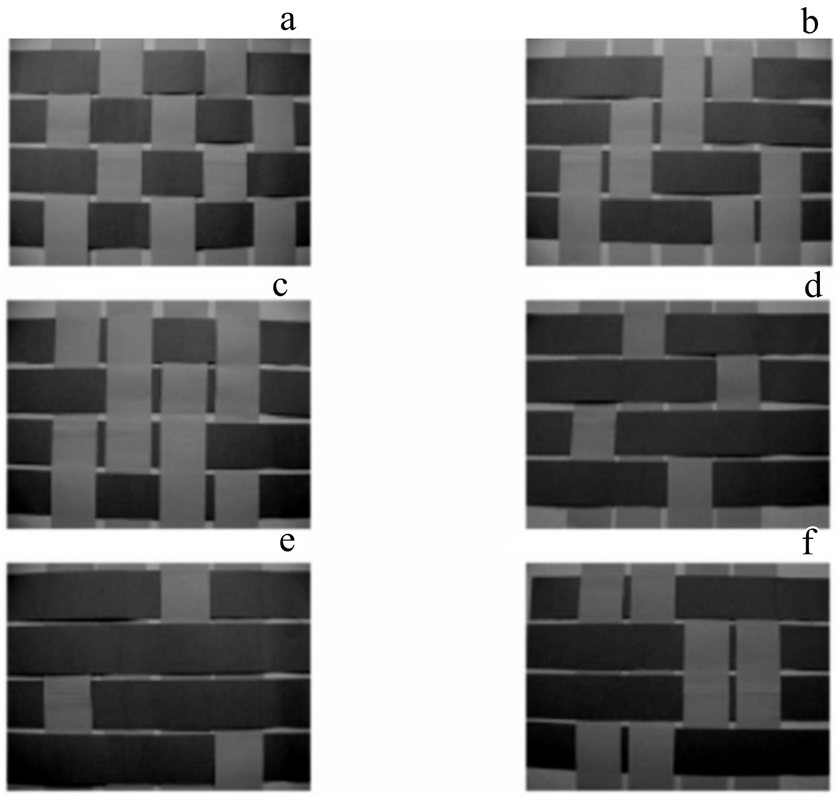

Fig. 2. Schematics of woven composites without matrix pockets: a — plain weave; b — 2×2 twill weave; c — 4-harness satin weave; d — 5-harness satin weave; e — 8-harness satin weave; f — basket weave.

weave can be 2D or 3D — the basic difference is that a 3D weave has additional yarns oriented in the through-thickness direction, which provides a 3D reinforcement. The fundamental 2D weaves most widely used in textile composites are plain, twill, and satin weaves [10]. Each of them is identified by their unique pattern of interlaced warp and weft yarns, as shown in Fig. 2.

Basically, any fabric can be identified by the pattern of repeating interlaced regions. There are two basic parameters characterizing a fabric: n_{fg}, which indicates that a warp thread is interlaced with every n_{fg}th fill thread, and n_{wg}, which shows that a fill thread is interlaced with every n_{wg}th warp thread. For nonhybrid fabrics, the geometric parameters n_{fg} and n_{wg} are equal ($n_g = n_{fg} = n_{wg}$) [11]. The simplest woven-fabric structure is the plain weave, in which the warp and weft yarns are interlaced in a regular sequence of one under and one over, as shown in Fig. 2a. In the twill weave, each warp yarn passes over two consecutive weft yarns and under the following weft yarn, resulting in a loose interlacing, as shown in Fig. 2b. Fabrics with $n_g \geq 4$ are called satin weave. Figure 2c, d, e, shows 4-harness ($n_g = 4$), 5-harness ($n_g = 5$), and 8-harness ($n_g = 8$) satin weaves. The basket weave, shown in Fig. 2f, is created from interwoven lengths of natural or man-made materials, such as cane, willow, linen, plastic, or wire, and has an allover texture resembling the weave commonly found in baskets.

Roze et al. [12] considered the 3D woven reinforcement as a potential load-bearing member for brittle-matrix composites. As the technology evolved, these materials more and more started to gain recognition as promising candidates for reinforcing polymer matrices [13-15].

Woven fabrics can also be classified depending upon the tightness and looseness of the interlacing yarns [3]. In a closed-packing weave, the fabric is woven tightly, providing almost no gap between adjacent yarns, while in the case of open-packing weaves, there are gaps between adjacent yarns, resulting in a loose weave.

Woven fabrics are anisotropic, flexible, and with distinct viscoelastic properties. Hence, their mechanical characteristics depend upon complicated combinations of fiber bundles, yarn spacings, stacking sequences, yarn sizes, fiber orientations, fiber

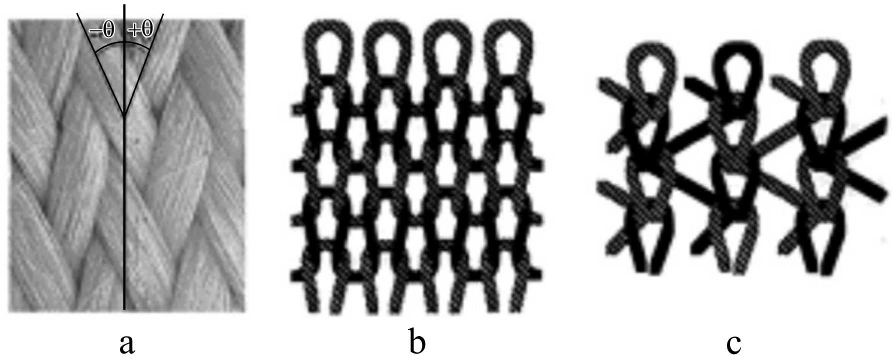

Fig. 3. Schematics of a biaxial braid (a) and weft (b) and warp (c) knitting.

architecture, and fiber volume fractions [16]. Due to interlacing of fiber bundles, woven fabrics offer extra-high resistance to damage growth and exceptionally high values of the strain at failure in tension, compression, and impact loadings [17]. They also possess good dimensional stability in the warp and weft directions, which results in a higher out-of-plane strength.

1.1.2. Braided fabric. The braid is a rope-like article made by interweaving three or more strands, strips, or lengths in a diagonally overlapping pattern. Braided fabrics are generally formed by the diagonal interlacing of a set of braided and axial yarns [17]. Usually, braided yarns are interlaced in either a 1×1 or a 2×2 pattern in ±θ directions, as shown in Fig. 3a. In practice, these fabrics are manufactured by using solid, horn-gear, two and four step, or track and column braiding methods [18, 19]. The mechanical properties of braided composites are sensitive to the braid angle, fiber volume fraction, yarn size, yarn architecture, and yarn spacing and depend upon the properties of fibers and matrix [19].

1.1.3. Knitted fabric. A knitted fabric is made by a continuous interlooping of one yarn system into vertical columns and horizontal rows of loops called wales and courses, which is performed by means of a meddler [20]. In weft knitting (see Fig. 3b), the yarns flow along the horizontal direction in the structure, whereas in warp knitting (see Fig. 3c), they flow along the vertical direction. This feature provides unique characteristics to knitted fabrics compared with woven and braided ones [21]. Knitted fabrics are used in technical textiles, such as artificial arteries, bandages, casts, composites, and so on. They offer a better resistance to impacts than woven-fabric composites [22]. The tendency of knits to resist wrinkling is the major factor boosting up their popularity.

2. Mechanical Modeling of Textile Composites

Several methods are employed for the analysis and mechanical modeling of textile structure. The mechanical modeling of such structures can be briefly classified as analytical and computational approaches, each having its own merits and demerits. Another important classification of the modeling aspects, which is based on the scale of models, is micromechanical, mesomechanical, and macromechanical modeling. The micromechanical modeling scale involves the study of orientation and mechanical properties of the constituent fibers. The mesomechanical modeling, on the other side, follows the concept of homogenization and evaluates the mechanical properties of a fabric unit cell, which in turn is used to calculate the effective material properties of the textile composite. Finally, the macromechanical modeling deals with predicting the mechanical properties of textile fabrics under complex deformations, assuming the fabric to be a continuous medium. The modeling hierarchy of textile composites, including its different stages, is sketched in Fig. 4.

At the initial stage of modeling, by using the homogenization technique, the properties of yarns are calculated on the basis of their architecture (the number and orientation of fibers and yarn type) and the properties of fibers. The properties of yarns serve as the input for the second modeling stage, where the unit-cell properties of a woven fabric are determined with

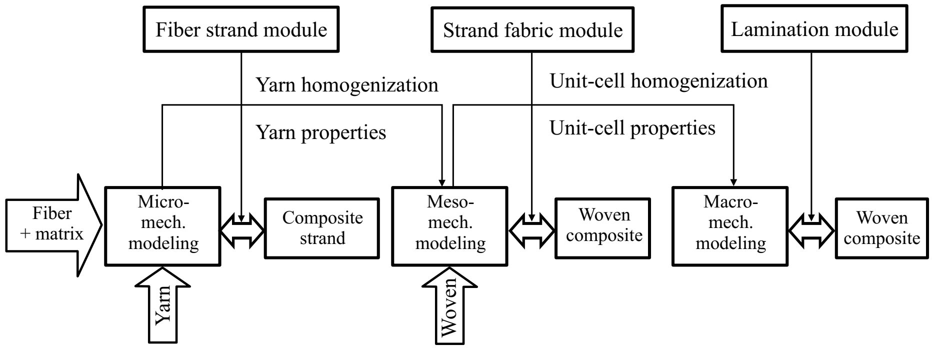

Fig. 4. Integrated textile modeling hierarchy.

invoking the homogenization technique. Finally, at the third modeling stage, based on outcomes of the preceding stages, the mechanical performance of the whole structure under complex deformations is predicted.

Many numerical methods, such as the boundary element method (BEM) [23], the finite-element method (FEM) [24], the finite-difference method (FDM), and meshless methods, such as the element-free Galerkin method [25], are available for analyzing orthotropic composite materials. Among all the methods, the FEM is most promising, because it allows one to analyze nonlinear systems with general boundary conditions and can be adapted to complex geometries. The successive paragraphs review this technique for modeling woven composites.

2.1. Finite-element modeling of woven composites

When the FEM is applied to textile composites, they are visualized as assemblages of unit cells, or representative volume elements (RVEs), interconnected at discrete numbers of nodal points. The unit cell can be considered as the smallest possible building block of a textile composite, such that the composite can be created by assembling the cell in all three dimensions [26, 27]. The third direction can also be repeated by addition of layers. The general procedure to predict the mechanical properties of a textile composite using the FEM includes (i) dividing the composite into repeating unit cells and calculating properties of the unit cell, and (ii) predicting the mechanical properties of the entire textile structure from properties of the unit cell. Hence, the ability of a FEA model to accurately predict the mechanical properties of a textile composite depends upon the accuracy of modeling of fiber geometry in the unit cell.

The modeling of woven-fabric composites has been an active area of research, because they provide desirable mechanical properties in both in-plane and transverse directions.

2.1.1. Elastic analysis of composites. The generalized Hook's law. The generalized Hook's law, relating stresses and strains for anisotropic materials can be written in the following contracted notation [28]:

$$\{\sigma_i\} = \{C_{ij}\}\{\varepsilon_j\} \quad (i, j = 1, 2, 3) \text{ (isostrain condition)},$$

$$\{\varepsilon_i\} = \{S_{ij}\}\{\sigma_j\} \quad (i, j = 1, 2, 3) \text{ (isostress condition)},$$

where $\{\sigma\}$ is the macroscopic stress vector, $\{\varepsilon\}$ is the macroscopic strain vector, $\{C_{ij}\}$ is the macroscopic stiffness matrix, and $\{S_{ij}\} = \{C_{ij}\}^{-1}$ is the macroscopic compliance matrix.

The unit cell, or the representative volume element, of a woven-fabric composite is orthotropic and homogenous, with the stiffness and compliance matrices given in the form [28]

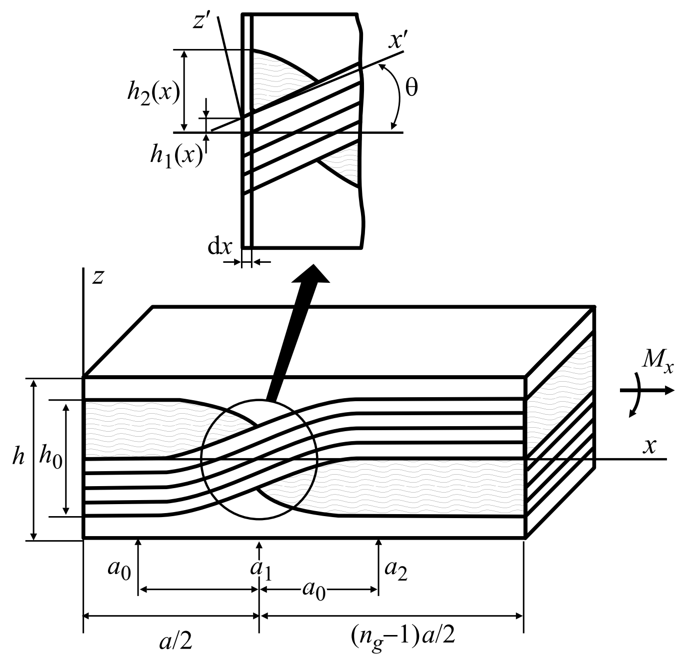

Fig. 5. Fiber crimp model: geometric parameters of the repeating unit of a woven composite [41].

$$\{C_{ij}\} = \begin{pmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{pmatrix},$$

$$\{S_{ij}\} = \begin{pmatrix} S_{11} & S_{12} & S_{13} & 0 & 0 & 0 \\ S_{12} & S_{22} & S_{23} & 0 & 0 & 0 \\ S_{13} & S_{23} & S_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & S_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & S_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & S_{66} \end{pmatrix}.$$

2.1.2. Elastic properties of woven composites. The engineering constants of a woven composite can be expressed by the following relations [29]:

$$E_x = \frac{1}{S_{11}}, \quad E_y = \frac{1}{S_{22}}, \quad E_z = \frac{1}{S_{33}},$$

$$\nu_{xy} = -\frac{S_{12}}{S_{11}}, \quad \nu_{xz} = -\frac{S_{13}}{S_{11}}, \quad \nu_{yz} = -\frac{S_{23}}{S_{22}},$$

$$G_{xy} = \frac{1}{S_{44}}, \quad G_{zx} = \frac{1}{S_{55}}, \quad G_{yz} = \frac{1}{S_{66}},$$

where, E_x, E_y, and E_z are Young's moduli in the *x*, *y*, and *z* directions; G_{xy}, G_{zx}, and G_{yz} and ν_{xy}, ν_{zx}, and ν_{yz} are the shear moduli and Poisson's ratios in the *xy*, *zx*, and *yz* planes.

2.2. Modeling the woven architecture

Pierce et al. [30] initiated the research in woven architecture and described it by tows of circular cross section. Later, Lomov et al. [31], Robitaille et al. [32-35], and Hofstee et al. [36, 37] proposed more suitable geometric descriptions, which contributed towards the modelling of textiles. In [31], a simple model of woven-fabric composites was developed and implemented in the WiseTex software in order to determine the geometry of a textile composite. An approximate description of the geometry was found by studying the interlacing pattern of weaves. Also, an analysis was performed to determine the minimum-energy configuration. Kregers and Melbardis [38] presented a model, based on a stiffness averaging method that included some geometrical aspects of yarn orientation, which was later extended to take into account the viscoelastic response [39] and further the elastoplastic properties [40].

Ishikawa and Chou [41] conducted the earliest research in woven-fabric composites and proposed three — mosaic, fiber undulation or crimp, as shown in Fig. 5, and bridging — models to predict their mechanical properties. The mosaic model is based on a procedure where the elastic stiffness matrices of a two-dimensional laminate are further simplified by considering two one-dimensional models — a parallel (isostrain) model and a series (isostress) model. However, fiber undulation is not considered in the model. The fiber undulation model, or UD crimp model, is an extension of the above-mentioned series model and is suitable for weaves with a small number of repeats. The in-plane stiffness obtained from this model is much lower than that given by the mosaic model. The previous two models are suitable only for UD composites and not for cross-plies. This drawback leads to the third model, the bridging model, which is a combination of series and parallel models and is generally applied to satin-weave composites, where interlaced regions are separated from each other. The bridging model is in good agreement with experimental results for satin-weave composites.

Ishikawa and Chou [42] also presented a laminated model. It is based on the assumption that the classical laminate theory (CLT), in which the overall behavior of a multidirectional laminate depends on the properties and stacking sequence of individual layers, is valid for every infinitesimal piece of the repeating unit of a woven lamina. However, the 2D extent of the fabric is neglected in the model.

Naik and Shambekar [43, 44] extended the UD models [42] to 2D elastic ones and developed parallel-series (PS) and series-parallel (SP) models, where the unit cell is divided into slices along and across the loading direction. These models are limited to uniaxial tensile loadings and do not provide an answer to the question when and why the SP or PS model should be used.

Hahn and Pandey [45] generalized the 2D models and predicted the linear thermal expansion coefficient α for a plain-weave fabric composite by choosing an appropriate representative volume element. The model also predicts the effective elastic moduli.

Raju and Wang [46] developed a number of theoretical models, which were later referred to as improved CLT models, valid for every infinitesimal element of the unit cell. They are able to predict Young's moduli, Poisson's ratio, and the thermal expansion coefficient for woven composites. The results were found to be in good agreement with other models, such as those proposed by Ishikawa and Chou [47].

Whitney and Chou [48] introduced the concept of microcells within the unit cell, in which fibers were presumed to form series of inclined plates. The model is able to predict the in-plane elastic property of 3D angle-interlocked textile preforms. However, according to the literature, less agreement with experimental results for satin weaves was found.

It can be observed that many of the above-mentioned models are based on the extension of the theory of laminated plates. They all basically consider the textile mat as a collection of laminated plates arranged in series, in parallel, or in some combination. Many researchers have reported FE-based numerical models that are based on fewer assumptions than analytical models and have the capacity to model the geometry of towpaths more accurately.

A strain energy approach, along with the FEA, for predicting the elastic constants of plain-weave fabric laminae was proposed by Zhang and Harding [49]. The principle drawback of this model is the fact that it can consider undulation only in one direction. To overcome this constraint, Naik and Shambekar [43] proposed an extension of the UD model and predicted the elastic constants for a 2D plain-weave fabric by including undulation both in the weft and warp directions. The lower and upper bounds of the elastic constants were estimated by dividing the unit cell into various sections.

Naik and Ganesh [3] suggested two models, known as the slice array model (SAM) and the element array model (EAM). In the SAM, the unit cell is sliced along the loading direction, and then each slice is recombined to determine the overall material properties. In the EAM, the unit cell is sliced across the loading direction, and unit cell properties are evaluated by assembling the slices either in series or in parallel. These models were used to predict the shear moduli and the thermal expansion coefficient, respectively, for various laminate configurations.

Later, Naik and Ganesh [50] introduced another theoretical method for a thermoelastic analysis of 2D plain-weave laminae. They considered 12 material systems (four of carbon/epoxy and eight of E-glass/epoxy) with different strand and weave geometries. Many factors, such as fiber undulation, weave geometry, the actual cross section of strands, the fiber volume fraction in strands, and gaps between two adjacent strands, were taken into account in their theoretical analysis. Using the CLT, they modeled the unit cell as an asymmetric cross-ply laminate consisting of three layers, one of pure matrix and two unidirectional laminae, and found two parameters — the actual cross section and undulation, defined by a suitable shape function, which were used in calculating the effective thermoelastic properties.

Soykasap [51] conducted an excellent research by analyzing and comparing the mechanical properties of one-, two-, and three-ply plain-weave composites on the basis of the rule of mixtures and UD composite beam and 2D mosaic models, respectively. The rule of mixtures, in conjunction with the CLT, proved to be a powerful tool in estimating the in-plane properties of composites, while for flexural properties, significant errors were reported to appear when the CLT was applied directly. The in-plane elastic properties of two- and three-ply woven composites were found to be the same as those of the single-ply one, whereas the flexural properties greatly depended on the alignments of fibers. The author also derived an analytical expression for the stiffness of each model.

An FE model for evaluating the mechanical properties of woven-fabric composites, in which the fabric was modeled by using beam elements, was proposed by Ichihashi [52] et al. The results obtained showed that the weaving density had not a great effect on the initial microfracture stress.

Sankar and Marrey [53] developed a unit-cell model for a textile composite beam and predicted its stiffness properties by assuming a homogeneous strain state in the material. An eight-node isoparametric plain strain element was used to model the unit cell.

Vandurzen et al. [54] developed a complementary energy model for 2D woven composites which captures the effect of both orientation and position of tow elements. This model uses a multilevel decomposition scheme to split the unit cell and a multistep homogenization procedure to predict the elastic moduli.

Amato [55], Ivanov et al. [56], and Rupnowski and Kumosa [57] successfully put to use the homogenization technique in evaluating the elastic behavior of woven-fabric textile composites. Another contribution to the modeling of plain-weave textile composite was made by Glassgen et al. in [58], where the unit cell was assumed to be consisting of elastic yarns and an isotropic matrix. A quadratic tetrahedral element was used in ABAQUS for calculations. In extension to the above-mentioned method, Glassgen et al. [59] introduced a method in which a detailed analysis of strains, stresses, displacements, and failure parameters was carried out using the FEM.

The upper and lower bounds for the elastic moduli of plain-weave fabric composites were given by Zhang et al. [60]. They developed a 2D undulation model by using the CLT.

Cox et al. [61] proposed a binary model based on the use of the finite-element package ABAQUS for 3D-woven textile composites. Two-node line elements were employed in the model for predicting the axial properties, while Poisson's ratio and the shear and transverse stiffnesses were found by using homogenous and isotropic eight-node finite elements.

A numerical procedure based on a global/local method for the 3D failure of plain-weave textile composites was suggested by Woo and Whitcomb [62]. The nodal displacements of macroelements were obtained from a global analysis using homogenized mechanical properties. Detailed information on stresses was obtained in a local analysis carried out by individually modeling the matrix and the fiber bundle. The load–displacement relationship for a 3D orthotropic woven-composite beam by

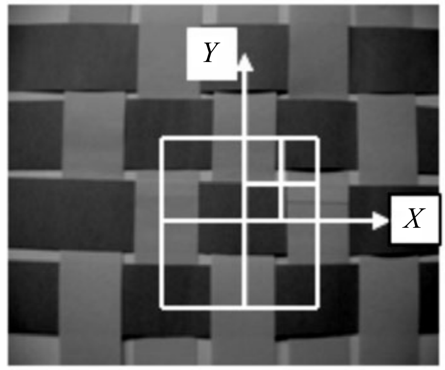

Fig. 6. Unit-cell model of a plain weave.

invoking the finite-element approach was predicted by Pochiraju et al. [63]. They developed a 3D model in ABAQUS by using 20-node 3D quadratic finite elements. Homogenized orthotropic material properties were employed throughout the analysis.

Walsh and Ochoa [64] adopted the unit cell approach to develop a mathematical model that, as they asserted, was able to predict the elastic properties of a woven composite. A 3D representative volume-element model was presented by Jiang et al. [65] in order to investigate the micromechanical behavior of woven-fabric composites. In this study, the standard homogenization technique along with isostress and isostrain assumptions was used for estimating their elastic properties. One fourth of the unit cell was homogenized in a local coordinate system, with assumptions of an isotropic matrix and a perfect interfacial contact. The predicted elastic moduli agreed with experimental results very closely.

Li et al. [66] formulated a unit cell of reduced size for plain-weave textile composites, which is shown in Fig. 6. The formulation consists of two parts — (i) identification of geometric symmetries and (ii) inclusion of these symmetries into appropriate boundary conditions. Different types of symmetries, such as translational, mirror, and rotational ones, were considered.

Sun and Vaidya [67] predicted the mechanical properties of UD fiber composites by analyzing an RVE. The elastic constants for the composites were determined by employing the strain energy equivalence principle in conjunction with a 3D FE analysis. The inhomogenous stress and strain fields of the model were related to the average stresses and strains by using the Gauss theorem and the strain energy equivalence principle. Good agreement was observed between the FE predictions and experimental data for boron/aluminum and graphite/epoxy composites.

Yang and Cox [68] presented a model based on the strain averaging technique in conjunction with a binary model, which proved to be in good agreement with full-field strain measurements for 3D woven composites in tension in the weft direction.

The analytical model developed by Yu et al. [69] on the basis of unit-cell geometry was able to predict the elastic properties of 3D woven composites. In this model, the linear elastic unit cell was divided into eight components depending upon the intersection of warp and filler bundles. The equilibrium and compatibility conditions were used to predict the elastic moduli E_x, E_y, and E_z, which were found to be in good agreement with data available in the literature. Hage et al. [70] proposed an analytical method in which either the *XYZ*-model or the volume averaging technique could be employed to compute the elastic properties of the RVE. The RVE was decomposed into warp tow, weft tow, binder tow, and matrix constituents, and then the global stiffness of the composite was computed using the volume averaging technique.

Kim et al. [71, 72] and Lee et al. [73] adopted a virtual material testing by using parallel multi-frontal solvers in conjunction with an FE analysis in order to predict the elastic properties of 3D woven-fabric composites. Kucher et al. [74] examined the deformation behavior of multilayered fiberglass plastics, reinforced with a fabric of satin weave, at room and low temperatures. Consistent values of their stiffness were found from tension and compression tests on specimens cut out from plates at angles of 0, 45, and 90° to the symmetry axes. The engineering constants E_1, E_2, G_{12}, and ν_{12} were successfully predicted by the model, but the prediction error of the constants G_{13}, G_{23}, ν_{31}, and ν_{32} did not exceed 12%.

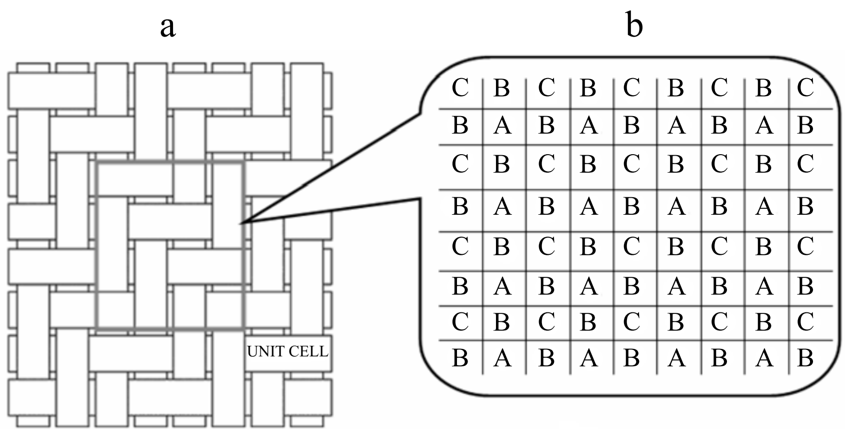

Fig. 7. Unit cell of a 2/2 twill-weave fabric (a) and its division (b).

Cox et al. [61], Thompson [75], and Whitcomb [76] developed several 3D finite-element models for a mechanical analysis of woven composites, but their drawback was high computational costs when applied to real structures. Therefore, a need arises for computationally more efficient models which could lead to reasonable results with a minimum effort. Also, most of these studies considered the plain-weave architecture and none of them examined 2/2 twill-weave or satin or any other complicated weave pattern. The following section of this review focuses on the computational effort made for complicated woven-fabric structures.

2.3. Modeling aspects of complicated woven-fabric architecture

Twill/satin fabrics offer improved bidirectional properties in their plane, which give rise to a higher specific stiffness and strength and improved dimensional stability as compared with UD composites. However, modeling of these complicated woven fabrics is still a challenging problem for the lack of understanding of their behavior under loading due to their complex tow architecture.

Aitharaju et al. [77] presented a new analytical/numerical model for estimating the effective stiffness properties of woven composites on the basis of a unit cell model. The unit cell of a woven-fabric composite is divided into three regions, characterized by no waviness (the cross-ply region; denoted A), waviness in one direction (the region where either warp or fill has undulation; denoted B), and waviness in two directions (the region where both warp and fill threads are undulated; denoted C), as shown in Fig. 7 in the case of a 2/2 twill-weave fabric. Based on the theory of effective moduli, the average stiffness properties of the elements are calculated and then the stiffnesses of each layer are found.

The average stiffness properties are taken as input data for computing the elemental stiffness matrix in the finite-element formulation. Then, dividing the problem into three subproblems and employing the superposition method, the elastic moduli and Poisson’s ratios in all three directions are estimated.

Ng et al. [27] predicted the in-plane elastic properties of 2/2 twill-weave T300 carbon/epoxy plates by utilizing a micromechanical 3D finite-element model of a single-layer unit cell in conjunction with the homogenization technique. The model developed was able to predict the elastic properties for other woven fabrics by choosing a suitable unit cell. The results obtained were very close to those found in experiments.

A general-purpose micromechanics analysis that discretely modeled the architecture of yarns in the representative unit cell of a textile was presented by Naik [78]. The model, which was meant to predict the overall, three-dimensional, thermal and mechanical properties, is based on the isostrain assumption and the stress averaging technique. It was also included into a

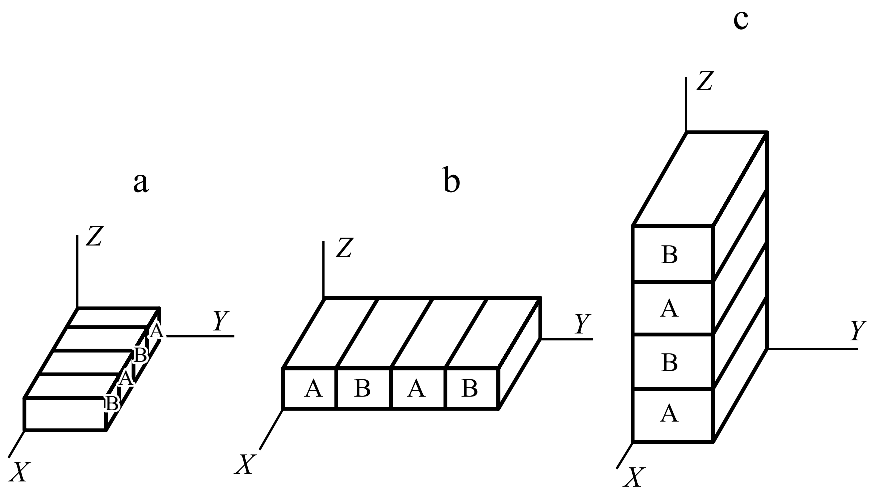

Fig. 8. *X* (a), *Y* (b), and *Z* (c) models.

computer program, called Textile Composite Analysis for Design (TEXCAD), to analyze plain 5-harness and 8-harness satin-weave composites along with 2D and 2×2 2D triaxially braided ones.

Tabiei and Jiang [26] developed a micromechanics model of composite materials for woven fabrics with a nonlinear stress–strain relation and separated out a representative cell. The cell was further divided into subcells, and averaging was performed to obtain the effective stress–strain relations. The properties obtained after averaging were entered into the finite-element code ABAQUS to perform a structural analysis. Tan and Steven [79] also proposed a full 3D modeling technique and carried out a FEA for four types of woven-fabric unit cells. A number of new 3D macro- and microblocks were introduced into this technique. A 20-node 3D brick element was used in the finite-element modeling of the blocks. The results obtained from this model correlated well with those available in the literature. Tan and his colleagues [80-82] also proposed a model for predicting the elastic and thermoelastic properties of 3D woven-fabric composites. Their approach is based on a mixed isostress/isostrain modeling scheme. In this model, the unit cell is segmented into a number of microblocks, which can be resin-impregnated warp, weft, or tow blocks. Thereafter, these microblocks are assembled according to the four possible combinations *XYZ*, *YXZ*, *ZXY*, and *ZYX* of the *X*, *Y*, and *Z* models developed by Tan et al. [79], which are shown in Fig. 8.

Kwon et al. [83] developed a micromechanical unit-cell model for 2×2 twill-weave fabric composites which could be implemented into a multilevel, multiscale technique for predicting the stiffness and strength along with progressive damage in composite structures. The basic framework of the multiscale micro/macromechanical model was previously developed by Kwon and his coworkers [84-87]. This model consists of three interconnected modules, as shown in Fig. 4. The fiber strand module, which was developed using a unit cell with four subcells (one representing the fiber and three the matrix), determines the effective material properties of the strand from those of constituent materials (the fiber and matrix). The strand fabric module relates the effective material properties of a UD composite strand to those of the 2×2 twill-weave fabric composite and consists of a unit cell which is subdivided into 77 subcells. The lamination module relates the effective material properties of lamina to laminate properties by using either lamination theory or the CLT, or a higher-order theory. The calculated properties are used in an FE analysis of laminated structures. The model developed correlates well with the results published for 2D and 3D micromechanics models.

Yushanov et al. [88] presented a stochastic modeling approach to examine the effect of randomly curved (imperfect) fiber reinforcements on the anisotropic stiffness characteristics of woven/braided composites. The mean values and standard deviations of stiffness characteristics were determined using random functions and a stochastic extension of the orientation averaging approach. The author successfully demonstrated this by determining the 21 stiffness, compliance, and engineering constants for a unidirectional fiber-reinforced composite, a 2D biaxial braided composite, and a 3D orthogonal woven composite.

A geometrical model of twill- and satin-weave fabrics for the calculation of elastic material properties based on the isostrain assumption was developed by Scida et al. [89]. Further, a stress analysis of these composites was also carried out [90] by using the isostress assumption. Hybridization was also considered in describing the architecture of these woven fabrics.

Chapalkar and Kelkar [91] found the effective modulus of a 2×2 twill-weave composite, but did not calculate the stresses and strains at the constituent level. The stresses and strains at this level were determined by Bohm et al. [92], Ghosh and Raghavan [93], but only for particulate and fibrous composites, not for wovens.

The modeling of textile composites was further simplified by researchers from the University of Nottingham by developing an open-source software package named TexGen [94]. The versatility of this tool can be judged by its ability to inculcate the processing, mechanical, and functional properties of textile composites and its applications into modeling the mechanics of dry fabrics, the flow of fluids through fabrics, and the mechanics of textile composites.

Jonathan J. Crookston et al. [95] predicted the deformation properties and the fatigue strength of 3D-woven orthogonal glass/vinyl ester textile composites by using an integrated scripting approach (TexGen) which allowed the realization of the entire modeling process (building a textile model + mesh generation + solution) without real-time intervention of the user. The results obtained were very close to available experimental data.

Hua Lin et al. [96] developed an efficient and successful realistic numerical technique, in conjunction with TexGen and ABAQUS, in order to predict the tensile, compressive, bending, and shear behavior of fabric composites, by designing a virtual unit-cell for plain- and twill-weave patterns. The cross section of yarns and the weave pattern were identified as crucial factors that influence the mechanical behavior of fabrics.

An alternative approach, called the 'voxel method,' was employed by Kim and Swan [97] with the aim to correctly model the complex 3D geometry of textile composites. This method originates from the domain of image processing techniques, requiring an automatic procedure for creating meshes.

S. A. Smitheman et al. [98] adopted the voxel-based homogenization method for estimating the thermomechanical properties of woven composites. The geometric model of unit cell was established by partitioning it into voxels (brick elements) and assuming the composite to be homogenous in each voxel. Further, by subdividing each voxel into cuboids and performing averaging, the effective properties of the voxels were determined.

The models proposed by Ishikawa and Chou [41], Naik and Ganesh [50], Sun and Vaidya [67], Ng et al. [27], Tan et al. [79-82], and Kwon et al. [83] for textile composites have all been verified experimentally.

3. Experimental Verifications of Models and Discussion

No model developed can be accepted until it is verified experimentally. The verification experiments must be performed as per the standard procedures such as ASTM D638M for tensile tests, ASTM D3410 for compression tests, ASTMD5379/ D5379M for shear tests, ASTM D790 for flexural tests, and ASTM D3479/ D3479M for fatigue tests. The corresponding test specimens are shown in Fig. 9.

A survey of the investigations carried out at the Institute of Polymer Mechanics of the Latvian Academy of Sciences to identify the recommended test methods for static mechanical testing of composites in tension, compression, bending, and shear on flat, tubular, and ring specimens was presented by Tarnopol'skii et al. [99]. The survey indicates the recommended specimen dimensions, the possible outcome, the standards accepted, and limitations for each of the above test in a tabular manner.

Fredrik et al. [100] in their research assessed the mechanical performance of a 3D woven-fabric composite by determining its tensile, compressive, out-of-plane, shear, and flexural properties. Flat beam specimens of rectangular cross section with four different configurations (3D, 2×2 twill, noncrimp $[0, 90]_{3s}$, and noncrimp $[90, 0]_{3s}$) were tested at room temperature. They concluded that the 3D woven material had better out-of-plane but worse in-plane properties than the traditional 2D laminates. The 3D and twill specimens were found to have lower in-plane stiffnesses and compressive strengths than NC ones. Young's moduli for all the specimens were evaluated between 0.2 and 0.3% strains.

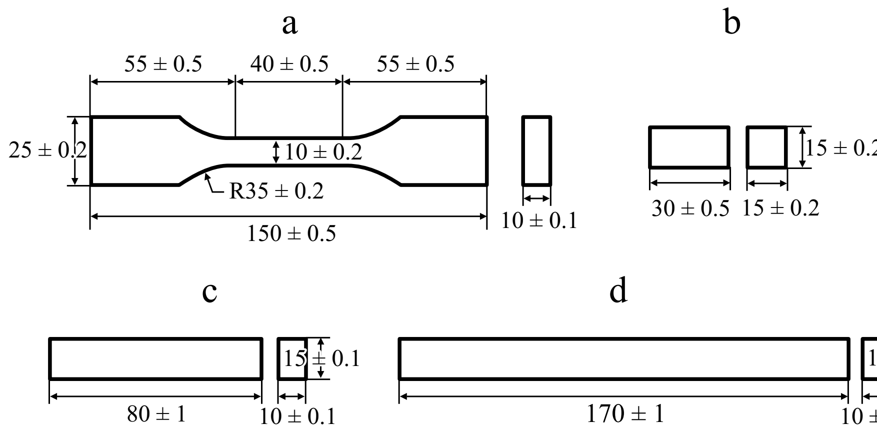

Fig. 9. Standard specimens for tension (a), compression (b), shear (c), and Poisson's ratio (d) tests.

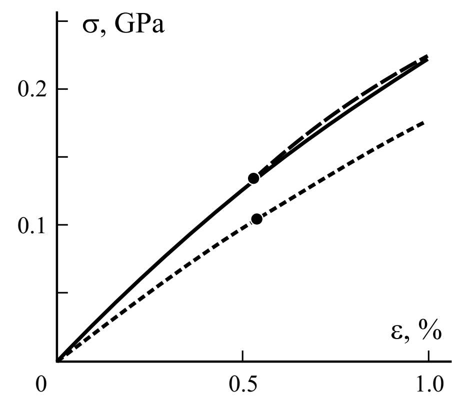

Fig. 10. Theoretical (lines) and experimental (dots) stress–strain relations σ–ε for a glass/polyamide composite.

The fiber crimp model developed by Ishikawa and Chou [41] is found to be effective for plain-weave fabrics, while the bridging model is valid for satin-weave ones because of the absence of regions of straight yarns surrounding an interlaced region in the plain weave. Therefore, the concept of bridging effect is not applicable to plain-weave fabrics, and the analysis must be based on the fiber undulation model, which predicts reasonable results in the case of plain weave. The crimp and bridge models were both used to describe the stress-strain state of woven composites after the fiber failure known as the knee phenomenon. The experimental data for an 8-harness glass fabric/polyamide composite are compared in Fig. 10 with calculations by the Ishikawa and Chou models [41, 42].

Naik and Ganesh [50] observed a good correlation between the CLT-predicted properties and experimental results for 12 material systems. The predictions were also compared with results given by other models, such as EAM-PS [3]. Calculations for balanced symmetric cross-ply laminates and UD composites by using the CLT were performed too. It should be noted that all the predictions were for laminae, whereas experimental results were for laminates. Young's modulus for the circular path was higher (42.9 GPa). Predictions by the closed-form analytical method gave higher value of Young's modulus (17.6-42.0 GPa) than those found by the EAM-PS model (17.3-42 GPa). A reasonable correlation for Young's moduli of the 12 material systems between experimental results (19.6-62.5 GPa) and predictions (19.5-42 GPa) were observed. In general, the values of G_{xy}, ν_{xy}, and α_x for sinusoidal and circular paths were practically identical. The analytical predictions for G_{xy} well agreed with experimental results (obtained in ±45° off-axis tension tests) for almost all the material systems, except for the first one because of compaction of layers in the actual laminate.

TABLE 1. Comparisons Between Experimental and Predicted Results [67]

Elastic constants	FEM, square array		FEM, hexagonal		Experiment	
	B/Al	AS4/3501	B/Al	AS4/3501	B/Al	AS4/3501
E_1, GPa	215	142.6	215	142.6	216	139
E_2, GPa	144	9.60	136.5	9.20	140	9.85
G_{12}, GPa	57.2	6.00	54.0	5.88	52	5.25
G_{23}, GPa	45.9	3.10	52.5	3.35	-	-
v_{12}	0.19	0.25	0.19	0.25	0.2977	0.3
v_{23}	0.29	0.35	0.34	0.38	-	-

TABLE 2. Predicted and Experimental In-Plane Mechanical Properties [24]

Properties	Prediction	Experiment
E_x, GPa	55.65	55.25
E_y, GPa	55.84	55.05
G_{xy}, GPa	4.41	3.55
v_{xy}	0.039	0.055
v_{yx}	0.040	0.060

TABLE 3. Summary of Comparisons between Experimental and Predicted Results [101]

Prediction	E_1	E_2	E_3	v_{12}	v_{13}	v_{23}	G_{12}	G_{23}	G_{13}
	GPa						GPa		
Prediction	40.97	47.30	-	0.035	-	-	-	-	-
Experiment	39.70	51.09	7.38	0.033	0.288	0.280	2.307	1.863	1.864
FEA	38.39	50.82	9.42	0.032	0.156	0.154	1.647	1.747	1.788
XYZ Model	52.92	59.79	14.53	0.034	0.215	0.216	1.840	2.233	2.389

TABLE 4. Comparison between Experimental and Predicted Results [102]

Model	Material	Experimental value		Analytical value		Kwon's prediction	
		$E_x = E_y$	E_z	$E_x = E_y$	E_z	$E_x = E_y$	E_z
[102]	S2/C50	28.7	-	30.6	-	28.5	-
[90]	E-Glass/Epoxy	19.24	N/A	19.54	10.93	19.67	9.21
[88]	Carbon/Epoxy	49.38	N/A	46.11	8.18	50.3	7.52

Sun and Vaidya [67] carried out a 3D FEA, at appropriate boundary conditions, for a typical RVE and predicted the elastic constants for two material systems (boron/aluminum and graphite/epoxy composites) with periodic square- and hexagonal-array arrangement of fibers. A comparison of predicted results with experimental data is seen in Table 1.

Ng et al. [27] obtained the in-plane elastic properties of a 2/2 twill-weave composite by experimental and numerical procedures. A comparison of the predicted and experimental in-plane mechanical properties can be seen in Table 2.

The four possible combination of *X*, *Y*, and Z models (*XYZ*, *YXZ*, *ZXY*, or *ZYX*) developed by Tan et al. [79-82] in order to determine the stiffness constants of 3D orthogonal woven-fabric CFRP composites were tested experimentally by Brandt

TABLE 5. Summary of Capacities of Various Mechanical Models

Ref./ Model	Dimen-sions.	Type of weave	C	α	STR	FEM	Limitations
[38, 42, 47] / Mosaic	1D	No yarn undulation	√	√	X	X	In-plane properties only
[38, 42, 47]/Bridge	1D	Satin weave	√	√	√	X	” ”
[38, 42, 47] / Crimp	1D	Plain weave	√	√	√	X	” ”
[45]	2D	” ”	√	√	X	X	Nonhybrid plain weave only
[43, 44]	2D	” ”	√	√	√	X	Nonhybrid plain weave only
[50]	2D	” ”	√	√	X	X	Computationally exhaustive
[67]	3D	UD	√	√	X	√	Computation cost
[48]	3D	Plain, Satin	√	X	X	X	In-plane properties only
[49]	1D	Plain weave	√	X	X	√	Undulation in one direction
[53]	3D	5-harness	√	√	X	X	-
[61]	3D	Plain	√	X	X	√	-
[77]	3D	” ”	√	X	X	√	Failed to predict G_{13}
[27]	3D	Twill	√	X	X	√	In-plane properties only
[78]	3D	5-8 harness	√	√	X	√	-
[79]	3D	Twill	√	X	X	√	Variations in the FEA and in the theoretical model
[81]	3D	Plain	√	√	X	√	-
[82]	3D	CFRP	√	X	√	√	Neglect of yarn waviness
[83]	3D	Twill	√	X	√	√	-

Notes: √ — predicted/used; X — not predicted/not used.

et al. [101]. The calculation and experimental results were found to be in good agreement. The summary of the comparisons for various stiffness constants is given in Table 3.

The unit-cell model developed by Kwon et al. [83] was validated by comparing its results with those of the 2D and 3D models considered in [88, 90, 102]. The comparison is given in Table 4.

The modeling capacities of various mechanical models are summarized in Table 5. These models have been tested for different weave architectures, from UD to 3D ones. The designations of columns C, α, and STR indicate whether the model predicts the full stiffness matrix, thermal expansion coefficient, or the strength.

4. Conclusions

A comprehensive review has been carried out to identify the modeling strategies for predicting the mechanical behavior of woven-fabric textile composites. The models reviewed can be classified in two categories — analytical and numerical ones. The analytical models, sometimes providing instantaneous results, are usually based on various assumptions related to stress and strain fields, while the numerical models, which depend upon the FE mesh, are free from such assumptions. Initially, the mosaic, fiber undulation, and bridging models seemed to be successful enough; later on, a great number of theoretical models based on an improved CLT were developed, and reasonable results were obtained. However, the finite-element method, along with a theoretical analysis, was accepted as one of the most powerful, cost effective, and computationally efficient analytical tools for predicting the mechanical properties of woven-fabric textile composites. Among various FE models, the models based on the unit-cell geometry or the representative volume element, in association with the homogenization technique, prove to be vital for analyzing the mechanical behavior of plain-, 2×2 twill-, and 5- and 8-harness satin-weave fabrics. However, these models can be improved still further. Some issues, such as a correct identification of the unit cell and the application of correct boundary condition to a chosen cell, need to be carefully resolved while carrying out an analysis. The models reviewed in this paper showed good correlation with experimental results or other equivalent models, but they could not predict the failure mode and the stress state at the microlevel. Lesser attention has been paid to the analysis of fabric deformations, despite their significance in the textile engineering domain. Hence, there is a need for more models based on the FE technique in order to obtain reliable predictions for the mechanical properties of textile composites and for the effects caused by variations in the major controlling parameters.

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