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A SURVEY OF MODELING FOR PREDICTING THE MECHANICAL PROPERTIES OF TEXTILE COMPOSITES

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ABSTRACT: Textile composite is one of the important materials used in industry and is made from textile substrates embedded in the matrices of different materials. However, due to its complicated microstructure, understanding of mechanical properties of textile composite materials is still in its infant stage. Recently, many researchers have contributed to develop finite element analysis (FEA) and theoretical analysis models for predicting mechanical properties of textile composite, and to study the variations of mechanical property with major architectural parameters. In this study, a survey of the research on the behavior and mechanical properties of textile composites of two common types, woven and braided, is presented. Various investigations, both finite element analysis and theoretical analysis methods, are described. Elementary models, laminate theory models, and numerical (finite element) models are included in this review. The predictive capability of various models, including earlier one-dimension (1D) 'mosaic model' and more recent three-dimensional (3D) models, are discussed in this review.

KEYWORDS: textile composites, finite element analysis (FEA) modeling, theoretical analysis method, and mechanical properties

INTRODUCTION

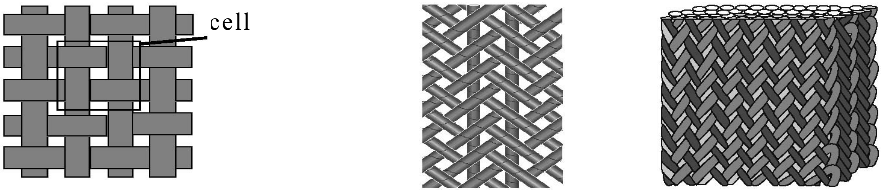
Textile composites are being widely used in advanced structures in aerospace, automobile and marine industry [1]. This is because they have favorable mechanical properties and attractive reinforcing materials with low fabrication cost and easy handing. Characterization of textile composites becomes very important to structural design. Textile based composite materials have received considerable attention in the literature in recent years [2]. In this study, a survey of some work on woven and braided textile composites is presented.

In the past 30 years, many researchers have continuously devoted their efforts to predicting mechanical properties of textile composites by making various assumptions. Earlier researches were carried out based on a large number of assumptions for simplifying the analysis procedures. These methods provided approximate estimation of mechanical properties, but they cannot be used to analyze variations of mechanical properties with some important architecture parameters due to introduction of oversimplified assumptions.

Finite element analysis is a useful and versatile approach used by many researchers to predict mechanical properties of composite materials. A number of FEA models have been developed to evaluate the effects of various fiber architecture parameters on mechanical properties of textile composites.

TYPICAL TEXTILE COMPOSITES

Textile composites are produced by impregnating matrix materials into their dry preforms to hold the multidirectional yarns together. This is generally done by using liquid molding techniques such as: resin transfer molding process (RTM), structural reaction injection molding (SRIM) and resin film infusion (RFI). There are two common types of textile composites, woven and braided. Several types of woven fabric pattern and braided patterns are shown in Figure 1.



(a) Plain weave (b) 2-D triaxial braid (c) 3-D braid

Figure 1. Textile material forms [3,4]

Woven fabrics are probably by far the most commonly used forms of textile composites in structural applications. They are produced principally by the multiple warps weaving method, and generally consist of two sets of interlaced yarn components, known as warp and weft (or fill) yarns according to the yarn orientation. Generally speaking, mechanical properties of woven fabrics are governed by: (1) weave parameters such as weave architecture, yarn spacing length (or pitch), fiber orientation angle, fiber volume fraction; (2) laminate parameters such as stacking orientation and overall fiber volume fraction.

Braided fabrics are one of the textile composites under consideration for aircraft applications that can be used at a lower cost and provide higher impact resistant/tolerant materials. The major parameters affecting the mechanical properties of braided fabrics include: (1) braid parameters such as braid architecture, yarn size, yarn spacing length, fiber volume fraction, fiber orientation angle; and (2) material parameters such as mechanical properties of the fiber and matrix. The major process parameters adjustable to control the microstructure of braids are speed ratio between braiding and taking up, linear density ratio of braider and axial yarn.

ANALYTICAL INVESTIGATION

To examine the stiffness, strength, and thermal expansion of woven fabric composites, Ishikawa and Chou and Ko proposed three analytical models, i.e., the mosaic model, the fiber undulation model, and the bridging model [5]. The mosaic model simplified the composites by omitting the fiber continuity and undulation (crimp). By assuming constant strain and constant stress, this model was effective in predicting the thermal expansion and thermal bending coefficients. This model could also be used for woven hybrid composites. The fiber undulation model considered the continuity and undulation of the fibers and led to a softening in the in-plane stiffness. A slightly higher in-plane thermal expansion coefficient and the same thermal bending coefficient were obtained by this fiber undulation model compared the those obtained from the mosaic model. The bridging model was specifically developed to estimate the elastic behavior of satin weaves where a fill yarn was interlaced with multiple warp yarns. This model simulated the load transfer among the interlaced regions in the satin composites. All models were two-dimensional and based on the classical laminate theory.

Yang et al. extended these models to predict the elastic properties of three dimensional textile structural composites based upon classical laminated plate theory and the fiber inclination model [6]. The idealized unit cell of the fiber inclination model treated all yarns as composed of straight segments oriented in different directions. However, the interaction among the yarns in the unit was not taken into account. Upon knowing the effective laminae properties with respect to the xy coordinate system, the local plate stiffness matrices $A_{ij}(x)$, $B_{ij}(x)$ and $D_{ij}(x)$ can be calculated from

$$\left[A_{ij}(x), B_{ij}(x), D_{ij}(x)\right] = \sum_{m=1}^{4} \int_{h_{m-1}}^{h_m} \overline{Q}_{ij}(\theta_\alpha, \theta_\beta)[1, z, z^2]dz \tag{1}$$

Ishikawa and Chou also studied the nonlinear elastic behavior of woven fabric composites. Three types of nonlinearity were considered; the shear deformation of the fill threads, the extensional deformation of the pure matrix regions, and the transverse cracking of the warp regions. In order to evaluate the theoretical predictions of the elastic moduli of the fabric composites, some experiments were conducted. Experimental results agreed with the theory for the eight-harness satin carbon/epoxy system, but not for the plain weave composites.

Another analytical solution was derived by Naik and Shembekar [7] to predict the elastic properties of woven fabric composites. In a one-dimensional model, The actual fabric geometry was not considered and either an iso-stress or iso-strain condition was assumed. However, in a two-dimensional model, the actual yarn and fabric geometry was considered and the iso-stress and iso-strain conditions were again used. A comparison of the in-plane elastic moduli between the unidirectional laminated composite and plain weave fabric composite was made by Shembekar and Naik. In another paper, they also examined the elastic properties of mixed composites, formed by a combination of unidirectional laminates and woven fabrics. Of course, they found that the mixed composites offered higher elastic properties than the equivalent unidirectional composites. The prediction of the off-axis elastic properties of plain weave fabric laminates was presented by Shembekar and Naik. They used a 2-d woven fabric composite model and found that the off-axis Young's modulus and shear modulus of plain weave fabric laminates were higher than those for the corresponding unidirectional laminates, bur the off-axis Poisson's ratio was lower. Naik and Ganesh also used the 2-D closed-form analytical method to predict the thermoplastic properties of 2-D orthogonal plain weave fabric composites.

Other approaches to predict the elastic properties of fabric composites have been proposed. Falzon et al. compared the capabilities of several techniques in predicting the stiffness of woven composites. There were three classes of models, i.e., elementary models, laminate theory models, and numerical models. Two elementary models were the Fabric Geometry Model and Angle Ply Undulation Model, which relied on a three-dimensional generalized

Hook's Law approach. However, elementary models were unsuitable for a strength analysis. Laminate theory models were based on classical laminate theory, used by Ishikawa and Chou as mentioned before. Numerical (Finite Element) models could be used for stiffness and strength predictions of 2-D and 3-D models.

Byun and Chou also reviewed recent progress in the modeling of the thermo-mechanical behavior of textile structural composites, including 2-D hybrid and non-hybrid woven fabric depending on the types of fibers, 3-D braided composites. And 3-D angle interlock fabrics which provided through-the-thickness reinforcement by interlacing yarns in the transverse direction. The elastic properties of 3-D braided composites were analyzed based on the energy method and the fiber inclination model. The modified fiber inclination model was applied to study the 3-D angle interlock fabric composites.

Byun et al. [8] analyzed two-step braided composites based on the lamination theory (for a micro-cell model) and the stiffness averaging method (for a macro-cell model). A two-step braided perform was composed of a set of straight axial yarns intertwined by braider yarns. Based on the macro-cell model, the effects of various braiding process parameters on the effective elastic properties were examined, such as the linear density ratio between axial and braider yams, the pitch length of the braider yarns, the aspect ratio of the axial yarns, and the aspect ration the braider yarns. In another paper, Byun and Chou compared the mechanical properties of two-step and four-step braided composites experimentally. Kostar and Chou described the simulation of two-step and four-step 3-D braiding processes. On the other hand, Soebroto and Ko presented an overview of the fabrication of 2-D braiding fabric.

Wu proposed a three-cell model [9], constructed on the basis of the microstructure analysis of braided structural composites which can be produced by four-step braiding (four-direction, 4D) without or with the addition of uniaxial reinforced yarns. From this model and with the aid of a yarn/matrix interfacial damage condition and porosity in the matrix, Wu studied the orthotropic symmetry, bimodulus and elastic-plastic behavior, braided preform and design formulae of 4D and 5D braided composites. In order to determine the engineering elastic constants, it is necessary to assume that the stiffness matrices for each cell can be superimposed proportionally, according to the contributing volume fraction, to form the total stiffness matrix as follows:

$$\left[\overline{C}\right]=\sum_{i=1}^{3}k_i\left[C\right]_i \qquad (i=B,\ F,\ R) \tag{2}$$

$$\left[\overline{S}\right]=\frac{1}{\left[\overline{C}\right]}$$

where $k_i=V_i/V$, $V=\sum_{i=1}^{3}V_i$.

Ma et al. determined the elastic properties of 3-D woven and braided textile composites based upon the fabric unit cell structure and the energy approach. The impregnated yarns (with matrix materials) were assumed as composite rods in the form of straight line segments. Based upon the interaction of yarns in two dimensions, the energy approach was formulated. Du and Ko also used a unit cell approach in developing a mathematical model for analyzing the structural geometry of 3-D braided composites. In the latter paper, they demonstrated that two-step braiding was a special variation of 3-D four-step braiding.

Furthermore, the mathematical model for studying the tensile stress-strain relationship of woven fabrics was developed by Jianlian. He used a nonlinear regression technique with an exponential function containing two parameters. To select the functions, he examined the tensile curves of samples. Keefe established a 3-D model of woven fabrics by treating a yarn as a solid model with a closed curve swept along a centerline path. The cross section of the individual yarn was assumed to elliptical to give an approximation of the effect of compressibility on the yarns. Wei and Chen derived equations for calculating the bending behavior of plain woven fabrics in the warp or weft direction by adopting a nonlinear law.

Ning and Chou formulated a closed-form solution of the transverse effective thermal conductivity of woven fabric composites. The analytical solution was based upon the constituent material properties, fiber volume fraction, and fabric parameters. Dadkhah et al. modified laminate models to include the tow waviness for predicting the in-plane elastic properties of triaxially braided composites.

Pochiraju and Chou presented analytical models to estimate the elastic stiffness and strength of 3-D woven and braided composites based on the geometric modeling of the fiber microstructure and the fiber and matrix material properties. They denoted the repeated geometric structures as macro-cells. The geometry within macro-cells was divided into unit cells that described the path of a single fiber yarn. Then, the yarn path was modeled with a function approximation such as a sine function for the undulation.

The unit cell continuum model, presented by Foye in 1990, was based on the principles of finite element analysis using heterogeneous hexahedral elements to predict the elastic properties of textile composites. However, sometimes this introduced mathematical instabilities in the solution if the stiffness of the fibers and matrix were different. Later, Gowayed et al. modified this model based on a micro-level homogenization at the integration points using a self-consistent Fabric Geometry Model. The fibers and the matrix were treated as a set of composite rods having various spatial orientations. Fiber architecture and material properties were related to the global stiffness matrix of the composite through micromechanics and a stiffness averaging technique.

Paumelle et al. analyzed the stresses induced inside woven composite microstructures by using the technique of homogenizing periodic media. They used double homogenization, i. e, homogenizing the properties of the yarn (fiber and resin) and homogenizing the properties of the fabric (yarn and resin). Dasgupta and Bhandarkar developed a 3-D finite element by using a two-scale homogenization theory to predict the linear thermomechanical properties of plain weave composites. The microscale was related to the characteristic dimension of the unit cell and the macroscale was related to the gross overall dimension of the structure. Then the volume averaging of stress and strain was used to calculate the homogenized effective overall properties of the composites. The elements were modeled as eight-nodded, three-dimensional, linear, isoparametric elements along with some wedge and tetrahedral elements at the yarn-matrix interfaces.

Ko presented a geometric model for 3-D braided composites using the concept of average cosine for presenting the yarn orientation to examine the tensile strength and modulus. Ko and Pastore also studied the structure and properties of 3-D fabrics formed by an irregular braiding process and developed a computerized design and analysis of braided performs. Soebroto et al. established design equations for braided composites by relating the braiding process parameters and yarn geometry to the braid geometry.

Sankar and Marrey [11] obtained a finite element model of the unit cell of textile composites to predict the flexural stiffness properties. They used a beam model similar to the 1-D fabric strip model presented by Ishikawa and Chou. Three linearly independent deformations, i. e., pure extension, pure bending and pure shear, were applied to the unit cell. Special constraint elements were used to apply periodic boundary conditions on the end faces of the unit cell.

Dastoor et al. developed a program called Fabric Computer Aided Design (FABCAD) to analyze uniaxial and biaxial load-deformation behavior of plain woven fabrics. The yams were assumed to be homogeneous, weightless, frictionless, and undeformed by shear forces, and to have circular sections that did not deform under external forces. However, they had finite bending rigidity and were linearly extensible. Naik also established a computer code called Textile Composite Analysis for Design (TEXCAD) to analyze a wide variety of fabric reinforced woven and braided composites, including plain weave, 2-D triaxial braided, and 3-D multi-interlock braided composites. A micromechanics analysis that discretely modeled the yarn architecture within the textile repeating unit cell (RUC) predicted the overall thermal and mechanical properties, damage initiation and progression, and strength of woven and braided composites. An iso-strain state assumption within the repeating unit cell was applied. For the input, the material parameters such as yarn size, braided angle, yarn crimp, and yarn spacing were needed. He found that the in-plane properties varied significantly with the braid angle and the strength decreased with increasing the braid angle of the axial yarn crimp angle. Masters et al. [12] used this TEXCAD program to examine the mechanical properties of 2-D triaxially braided composites. A parametric study was conducted on two categories, i. e., primary braid parameters (yarn size, braid angle, axial yarn content) and secondary braid parameters (axial yarn spacing, braid yarn crimp angle zero degree yarn crimp angle). Zhang et al. noted that the braid parameters were related to one another.

Raju and Wang [13, 14] used classical laminate theory models to analyze the elastic properties of woven fabric composites. In this study, they included the resin properties in the model. The undulation of both the warp and fill yarns was treated as they were in the unit cell; there was no assumption to simplify the analysis. Whitcomb and Woo [15] developed the direct stiffness method for finite element analysis of textile composites. They also proposed a technique for calculating the stiffness matrix for a reduced substructure.

Marrey and Sankar established micromechanical models for predicting the stiffness and strength properties of textile structural composites. They developed a finite element code, called TE-10 (microtech-10), predict the textile composite properties. Also, they developed another code, called TE-20 (microtech-20), implementing the Selective Averaging Method. This method used an approximate analytical method, in which both stiffness and compliance coefficients were averaged selectively depending on a more realistic assumption of either iso-stress or iso-strain. They assumed a repeating unit cell shape of the composite as a rectangular hexahedron. Cox et al. [16] presented a binary model (a finite element model) of 3-D woven composites to calculate the elastic constants, strength, notch sensitivity, and fatigue life by using two types of elements. The yarns were modeled using two-node line elements and the rest of the medium by eight-node solid elements. They also applied Monte

Carlo simulations to predict failure mechanisms in angle and orthogonal interlock woven composites under monotonic and fatigue loading.

Chapman and Whitcomb examined the effect of assumed tow architecture on the predicted moduli and stresses in plain weave composites by using 3-D finite elements. They assumed a sinusoidal yarn path and a lenticular cross section. They studied two types of tow architectures, the translated architecture by keeping the section vertical along the tow, path and the extruded architecture by keeping the section perpendicular to the tow path. At a high waviness ratio there was a significant difference between them. Hewitt et al. established a computer modeling of woven composites. The model, providing a 3-D representation of any single layer weave geometry, comprised a series of blocks containing a warp and weft crossover area. When the blocks were assembled in the correct orientation, they joined together to form a weave pattern.

Pastore et al. [17] developed Textile Geometry Models for characterizing the geometry of yarns within the composites. Using this model in a 3-D finite element analysis, Glaessgen and Griffin investigated the displacement, stress, strain, failure parameters, and effects of boundary conditions on the response of woven textile composites. They used the IDEAS and ABAQUS programs. Thermal and mechanical loading were also considered. Shkoller and Hegemier derived the governing equations of plain weave composites by using convergence results developed for a periodic function. Whitcomb et al. [18] evaluated the global and local stresses of textile composites by using the boundary model displacement and forces from the global analysis to determine the appropriate loading conditions for a refined local model. They applied a finite element model. Homogenized engineering properties were utilized to obtain the global solution, but they gave significant errors in the prediction, especially at the boundaries.

Lei et al. used a finite cell method to analyze the mechanical behavior of 3-D braided composites. In this study, they treated the unit cell as a space-truss structure. This method was based on the principle of virtual work and structural truss analysis. Branch et al. established a 3-D tow inclination model to calculate the elastic constants of 2-D and 3-D woven and braided composites based on the oriented inclined tows and interstitial matrix. They wrote a program called Fortran Computer Code Towinc-3D for the analysis. The elastic constitutive matrix of the composite was derived from the 3-D stress transformation and the iso-strain condition.

Recently, Okumura et al. discussed an optimum design method of a woven structure of 3-D fabric composites by combining genetic algorithms and finite element analysis. The objectives of the optimism design were minimization of the density of 3-D composites and maximization of the stiffness or strength of 3-D composites for several loading directions.

CONCLUDING REMARKS

This literature review shows that finite element analysis (FEA) and theoretical analysis methods become one of the powerful tools for studying the mechanical properties of textile composites. The microstructure of textile composites is very complex in nature and the parameters controlling the mechanical properties are numerous, therefore it is difficult to model the textile composite architecture in detail using FEA and theoretical methods. Further investigations of textile composite are needs.

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