Micro Mechanical Model of 3D Woven Composites

ZHOU Chu-wei
(*College of Aerospace Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China*)

Abstract: A combined beam model representing the periodicity of the microstructure and micro deformation of 3D woven composites is developed for predicting mechanical properties. The model considers the effects of off axial tension/compression and bending/shearing couplings as well as the mutual reactions of fiber yarns. The method determining microstructure by using woven parameters is described for a typical 3D woven composite material. An analytical cell, constructed by a minimum periodic section of yarn and interlayer matrix, is adopted. Micro stresses in the cell under in-plane tensile loading are obtained by using the proposed beam model and macro modulus is then obtained by the averaging method. Material tests and a 2D micro FEM analysis are made to evaluate this model. Analyses reveal that micro stress caused by tensile/bending coupling effect is not negligible in the stress analysis.

Key words: 3D woven composites; micro mechanics; bending/shear coupling; off axial effect; combined beam model

三维机织复合材料的一个细观力学模型. 周储伟. 中国航空学报(英文版), 2005, 18(1): 40–46.

摘　要: 根据三维机织复合材料中细观几何和变形的周期性, 提出了一种反映细观周期约束条件的组合梁单元模型, 该模型既考虑了纤维束的偏轴拉压效应, 又考虑了纤维束的弯/剪耦合效应和纤维束之间的相互作用, 可以描述纤维束和基体中的细观应力分布。针对一种典型的三维机织复合材料, 研究了根据编织参数确定材料细观结构的方法, 在此基础上选取材料中最小周期的一段纤维束作为分析胞元, 用上述模型分析了面内拉伸荷载下胞元中各相材料的细观应力, 进而得到材料平均的宏观模量。材料试验和二维细观有限元分析证明了本模型的可靠性。研究表明, 三维机织复合材料中, 纤维束拉、弯耦合效应引起的细观应力在应力分析中不可忽略。

关键词: 三维机织复合材料; 细观力学; 弯/剪耦合; 偏轴效应; 组合梁单元
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3D woven composites have the advantages over laminate composites in higher damage tolerance and impact resistance due to reinforcement in the thickness direction. They have been finding increasing applications in high performance structures such as aerospace, automobile, and sports equipment.

The mechanical properties of 3D woven composites depend upon properties of constituents, fiber volume fraction, microstructure and waviness ratio of fiber yarns. Several models, classified into two categories, analytical estimation or numerical prediction, have been advanced to predict mechanical properties of 3D woven composites[1-13]. Most analytical models are based on classical laminate theory[2-8]. For example, Whitney and Chou[4] simplified the crimpled fiber yarns in 3D woven composite as inclined straight laminates along the fiber yarn thus the curvature effect was ignored. Yang[5,7] and Yan[6,8] took curvature of fiber yarn into account in their model by viewing fiber yarns as curved laminate, and the average elastic properties were then obtained by integrating stiffness constants along crimple yarn. Yi and Ding[9] defined four sub-unit cells, named warp, filling, stuffer and binder for textile composites, and the elastic properties of several types of 3D woven composites were obtained by combining these four sub-unit

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cells in patterns representing the microstructures. It is found that, however, the existing theoretical models, including those mentioned above, do not take the bending stress of yarns into account, except in Chou's work of studying plane woven composites[10, 11].

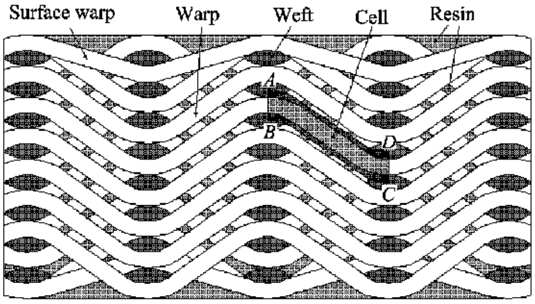
With respect to the numerical category, FEM is most commonly used. For example, a binary model was suggested by Cox *et al*[12], in which fiber yarns were modeled by bar elements and effective matrix by brick elements. Though 3D brick elements are widely used in analysis of plain woven and 3D braided composites, its applications to 3D woven composites have been rarely seen thus far.

In this paper, a shear/bending coupling combined beam model representing periodic restrain condition of 3D weave composites is suggested. The element contains two phases, one is a fiber yarn and the other is resin, or transverse fiber yarn, or the combination of them. In the model bending and shear stresses introduced by tension/bending coupling of fiber yarns are considered. Due to the capability of describing detailed micro stress, this model has potential to be further developed for strength and damage analysis of 3D woven composite.

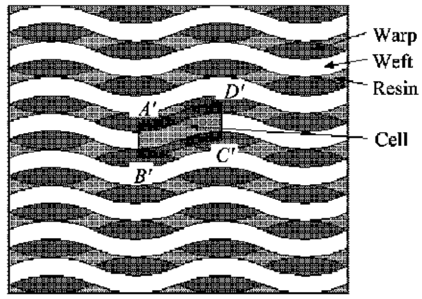
1 Combined Beam Model with Periodic Restrictions

1.1 Bending/shear coupling of combined beam elements

The microstructure of a typical 3D composite is shown in Fig. 1. In the interior region, the adjacent warps (or wefts) are parallel to each other and packed periodically. For convenience, in the weft



(a) Cross section of weft



(b) Cross section of warp

Fig. 1 The microstructure of a 3D woven composite

cross section plane shown in Fig. 1(a), warp is referred as phase one while weft and resin as phase two. In warp cross section plane depicted in Fig. 1(b) the phase one becomes weft while warp and resin compose phase two. In micro view, both structure and deformation under in-plane loads are periodic. Therefore, repeated unit cell method is used in mechanical analysis. The practical analysis cell is adopted as a half part of the smallest periodic section of the material due to symmetry. The dark color region of $ABCD$ in Fig. 1(a) is the analysis cell in warp direction, while the region of $A'B'C'D'$ is the analysis cell in weft direction. The cells contain a half wavelength of the fiber yarn and two layers of a half thickness of phase two. The fiber yarns are in waves thus introduces bending under in-plane tensile or compressive loading. Deformations of analysis cell include both off axial tension/compression and bending characterized by models of unidirectional composites and beams, respectively. A beam element model combining two phases is proposed herein. The element is composed of a section of fiber yarn and two layers of a half thickness of phase two. For simplicity, the beam element developed here is straight. Therefore, the curved cell should be segmented into a series of these straight beam elements. The components of phase two in an element depend on the element's location in the cell. As shown in Fig. 1, the beam's phase two contains only resin if it is in the central part, while the element's phase two may include transverse fiber yarn only or the combination of fiber and resin if it is located near the end.

As shown in Fig. 2, the bending of fiber yarn