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Computational geometrical and mechanical modeling of woven ceramic composites at the mesoscale

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ABSTRACT

Woven composite materials are receiving particular attention in a wide range of specialized aeronautical applications. Reliable numerical prediction tools based on computational modeling are required to quantitatively characterize the role of the microstructure and damage mechanisms at the mesoscale. In this paper, such a computational strategy is illustrated on a generic SiC/SiC plain weave composite with chemical vapor infiltrated matrix. Matrix and tows damage mechanisms are respectively introduced through the use of an anisotropic damage model, and an homogenized model based on a micromechanical model on the fiber scale. The latter is presented in this paper for the first time. Particular attention is paid to the generation of accurate hexahedral meshes, compatible at the tow–tow and tow–matrix interfaces. The mesh quality is analyzed using an error estimator variable based on the strain energy density. Damage predictions obtained using tetrahedral and hexahedral meshes are compared for basic loading cases, illustrating the need for using high quality meshes in the growing community of woven composites computational modeling.

1. Introduction

Composite materials manufactured using textile architectures are receiving a growing interest in the field of advanced structural applications [1]. One of the reasons is related to the fact that the microstructure of fiber preforms can be tailored to satisfy the specific needs for mechanical performance. Other advantages include the ease of handling for automation, the ability to generate complex shapes, and the reduction of delaminations effects thanks to the architecture of the fabrics. However, their mechanical in-plane properties, stiffness as well as strength, are lower than those of UniDirectional (UD) composites. The reason for this drawback is the generally higher fiber undulation, which is due to the textile fiber architecture and to the fabrication process.

Three-dimensional multiscale modeling of the mechanical behaviour of woven composite materials poses a challenge to the development of reliable finite element models able to predict the macroscopic structural response of the mechanical part [2,3]. At the macroscale level, which is the scale where the whole mechanical part is considered, the fabric is considered as an anisotropic continuous material exhibiting mechanical properties inherited from its meso- and microscale [2,4]. At the mesoscopic level, which is the scale of a yarn, the influence of the woven architecture on stress distribution and mechanical properties is considered. Patterns for woven fabrics are defined by the smallest Representative Volume Element (RVE), if it exists, which describes the interlacing of the warp and weft yarns. Fabrics in the dry form are then consolidated with resin via Resin Transfer Molding (RTM), or other processes. Among them, the Chemical Vapor Infiltration (CVI) technique has been studied since the 1960s, and has become quite important commercially for high temperature structural applications [5]. CVI is a slow process, and the obtained composite materials possess some residual porosity and density gradients. Despite these drawbacks, the CVI presents a few advantages. For instance, the low temperature of the process (900–1100 °C) minimizes fiber damage, and since densification is conducted under essentially no external pressure, fiber arrangement is undisturbed during the process.

Over the years different tools for the geometric modeling of the preform have been combined with finite elements strategies to obtain an appropriate mechanical characterization of the mesoscale. A short overview of the most important contributions in the field

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of Ceramic Matrix Composites (CMCs), elaborated using CVI, is provided herein. TexGen [6] and WiseTex [7,8] represent the current state-of-the-art in generalized textile modelers. Even though their primary application is in the design and manufacture of fiber-reinforced polymer matrix composites, Nemeth et al. [9] compared the two finite element softwares to gain an understanding of their current capability and to assess the potential suitability of these software programs to efficiently generate finite element models of a broad family of woven architectures of CMC. This was done for both idealized weaves (without defects) as well as weaves with various introduced defects. Tetrahedral meshes were used. Both TexGen and WiseTex were useful for generating solid models of the tow geometry. However, it was concluded that none of the programs at their current state of development was able to provide a complete generalized capability to model a CMC. Moreover, there was a lack of consistency in generating well-conditioned finite element meshes of the tows and matrix since interpenetrations between the meshes were generated. A solution often adopted, mainly in the modeling of polymer matrix composites, is to insert a thin matrix layer between all yarns [8,10–12], in order to create independent yarn surfaces. These surfaces and the enclosed can be easily meshed using automated meshing tools. However, the thin matrix layers cause either bad quality elements or a very fine mesh size within the layers, and a reduction of the fiber volume fraction that does not correspond to reality. FE meshes without these artificial matrix layers have been created up to now only for some specific idealized geometries [13,14]. A very flexible method to mesh complex geometries and quite used to avoid problems of interpenetration, especially in case of complex preforms, is the voxel method [15]. The main advantage of this method lies in its simplicity since the meshing can be carried out in few operations, whatever is the complexity of the geometry. However, it can provide an extremely rough and mesh-dependent representation of local stress and strain fields, especially at material interfaces, leading to bad predictions of damage mechanisms.

A procedure worth being mentioned to develop automated finite element model generation of 2D textile CMC with progressive damage/failure models has been proposed by the Charalambides group at the University of Maryland Baltimore County. Of particular interest is the work of Rao et al. [16] who showed results from extensive simulations regarding elastic and matrix cracking properties for plain weave, 4 Harness-Satin (HS), 5HS, and 8HS architectures. A full 3D finite element model of the RVE, roughly represented, was developed containing the individual tows and matrix. The layered matrix model was developed to study the fiber tow architecture and matrix material deposition via the CVI technique. An interesting feature is the modeling of the large scale void (as a central hole) that served as a region of stress concentration such that damage was always predicted to initiate at this location. A localization procedure from the micromechanical models allowed for determination of stresses within individual constituents and respective damage evolution through loss of effective stiffness. It was concluded that a good approximation of the overall response of the material could be obtained, however, their specificities could not be taken into account.

Another contribution is the one of Couégnat et al. [17] who proposed a multiscale model for the mechanical characterization of woven ceramic composite materials based on a physical description of the reinforcement, the properties of the constituents and their damage mechanics for the derivation of the effective macroscopic constitutive behavior. At the mesoscale, the geometry of the woven reinforcement is modeled from the yarns interleaving sequence and their geometrical properties. Then, the total bending energy of the textile reinforcement is minimized to calculate its internal geometry in a relaxed state. The matrix is made of a thin layer deposited almost uniformly around the yarns. Boolean operations, performed directly on the FE mesh of the representative unit cell, are used to generate the final entities, thus avoiding interpenetration between the parts. Afterward, the damage identified experimentally [18] was duplicated in the finite element mesh by creating cracks at the different scales to identify the damage effect tensor. Couégnat's model probably represents the most accurate approach currently available. However, an idealized geometry of the textile is adopted at the mesoscale, *e.g.* uniform cross section of the yarns. Moreover, a layer of matrix is introduced between the yarns in contact to simplify the meshing process and avoid interpenetration. Additional interesting contributions can be found in [9].

The purpose of this paper is to present a strategy for the mesoscale modeling of woven ceramic composites with chemical vapor infiltrated matrix. The attention is restricted to the presentation of the numerical tools developed and the illustration of the procedure. This is done considering an idealized two-dimensional RVE of plain weave textile architecture. The key points of the strategy are overviewed in Section 2, in particular the steps concerning the geometrical construction of the RVE, and the subsequent generation of the finite element model. The damage models adopted in the RVE are presented in Section 3. Then, numerical results concerning an idealized RVE of a SiC/SiC plain weave textile architecture subjected to uniaxial tension are shown in Section 4. Finally, conclusions are drawn and future possible developments are proposed in Section 5.

2. Geometrical modeling on the mesoscale

The proposed procedure is composed of two main parts. The first part concerns the geometrical modeling of the RVE of a CVI textile structure, and it was developed within the CATIA V5 framework. The second part concerns the finite element model and analysis of the RVE, and it was performed using Abaqus/Standard 6.10. A summary of the different steps of the procedure is provided below.

2.1. Representative Volume Element (RVE)

The first step concerns the geometrical model of the textile reinforcement. Some of the mesoscopic models proposed in the literature have been reviewed in the previous section. A modeling strategy of particular interest is the one proposed by Hivet and Boisse [19] who developed a consistent 3D geometrical model of 2D fabric elementary cells for appropriate finite element simulations of the forming process prior to matrix impregnation. They performed experimental observations using different optical processes to determine real yarn geometry in different cases of yarn structure and weaving. One particularity of this model is that it ensures a realistic contact surface between yarns without interpenetration for all types of weaving. Another particularity of the model is that the section shape varies along the trajectory, so that the influence of contact between yarns on their cross section shape can be taken into account. Moreover, their geometrical model is built using the CAD software CATIA V5. The advantage of using CATIA V5 is that any kind of geometry can be generated and improved. Their strategy was adopted in the present procedure to create the fabric elementary cell.

Then, the matrix has to be introduced on the fabric. Two assumptions are made. First, it is assumed that the geometry of the reinforcement does not change after the matrix infiltration. Second, the matrix has a constant thickness all over the reinforcement. These hypothesis are clear limitations of the current model, but more realistic hypothesis could be made (see *e.g.* [20]) and more involved technics could be used (see *e.g.* [21]) while still using most of the strategy presented here. Nevertheless, this