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Smoothing artificial stress concentrations in voxel-based models of textile composites

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ABSTRACT

Voxel meshing is an effective method to discretise the internal architectures of multi-phase materials. Spurious stresses are however introduced in the vicinity of a multi-material interface due to the stepped, block-like representation of smooth boundaries. A stress averaging technique is presented to eliminate artificial mesh-imposed stress concentrations. The effect of the local averaging domain size, averaging weight function, and mesh dependence is explored. The voxel finite element method with stress averaging is then further developed to study progressive damage propagation and failure analysis of composites. An additional control, based on the failure plane angle of each element, is included to ensure propagation of damage in the direction dictated by the physics of the process rather than mesh artefacts. It is found that the stress averaging technique is an effective way to alleviate local stress concentrations and can ensure correct damage and failure mode prediction when compared to a conformal mesh.

1. Introduction

Finite element (FE) analysis is a powerful way to study the mechanical properties of textile composites, such as stiffness, nonlinear progressive damage, strength and fatigue [1–3]. However, if the internal geometry of the composite is too complex, it is difficult to generate a consistent conformal mesh of the interacting composite components. In textile composites, the meso-scale geometry configuration is complex due to yarns interacting with each other during preforming, draping and consolidation [4]. The resin rich zones between yarns are irregular and highly distorted with extremely high aspect ratios. Usually, a large number of tetrahedral elements are used to discretise such complex geometry, but it is difficult to guarantee the mesh quality, or meshing such shapes can be beyond the capability of state of the art automeshing programs. Therefore, alternative methods have been proposed in the literature to solve the problem of mesh generation for composites with complex meso-scale geometry.

In order to overcome these difficulties, Cox et al. [5,6] proposed the FE based binary model to study the elastic and nonlinear deformation of 3D interlock woven textile composites. In this model, the yarns were represented by two-node line elements without explicit 3D morphology meshing. Yarn nodes were connected with the effective medium nodes via coupling springs. The advantage of this model is the ability to analyze the behavior of large specimens. Its weakness however is that it cannot obtain the local detailed stress fields for the yarns. Following on from Cox's binary model, other methods have been proposed such as the independent mesh method (IMM) [7] and the domain superposition methods (DST) [8,9] with direct 3D meshing of the yarns coupled to a matrix material. A common aspect of these methods is that yarns and global volume are meshed independently. However, the connection constraint conditions between the individual yarns and global volume can differ. Methods [7–9] all consider yarns with 3D morphology, meshed explicitly, and can tolerate small errors in the detailed yarn geometry. The weakness of these methods is that they utilize penalty functions to approximate the strain field jump at the interface and these penalty functions may increase the computational burden.

Some novel elements have also been developed to describe the interface strain discontinuity problem in order to circumvent the mesh generation difficulties. One approach, called the Mixed FE Method (MFEM) [10], also uses regular meshes, in which interfaces between the different constituents are not required to coincide with element boundaries. If an element is cut by an interface, the integration points at the two sides of the interface have different material properties. This numerical strategy can calculate the homogenized parameters and be extended to handle progressive damage analysis. However, due to the different materials at

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different integration points within one element, the large variation in gradients of local displacement and stress can result in a slow rate of convergence for the MFEM. Another potential strategy originally proposed by Belytschko and Black [11] is the extended finite element method (XFEM), which is based on the concept of partition unity to analyze mesh-independent crack propagation in heterogeneous media with phase boundaries. Belytschko et al. [12] and Moës et al. [13] utilized voxel/pixel based meshing to combine implicit surface descriptions of engineering components in a structured FE analysis. An arbitrary mesh was created, similar to the voxel method. A level set function was then calculated at the nodes of elements to determine the location of the implicit surface. Then enrichment functions were used to modify the structured FE approximations of the displacement field so that a strain field jump at the phase boundary was modeled. However, this method becomes difficult to use for multiple and possibly very complex enrichment schemes necessary for characterizing multiple yarn junctions and sharp corners.

Voxel meshing in contrast to these more advanced numerical formulations is a conceptually straight forward technique to discretise complex geometry of composites, especially for textile reinforcement. A voxel mesh uses a regular grid of elements and the internal yarn architecture is defined by assigning different material properties to the individual elements. Voxel meshes for woven composites with complex geometry can be obtained directly from textile pre-processors such as Texgen [14]. One of the main limitations of this technique is that the mesh size needs to be much smaller than the features of interest, such as the cross section dimensions of yarns. Voxel meshes can be introduced in IMM, DST, MFEM and XFEM, and also can be directly employed in standard FE to study the effective properties [15,16] and progressive damage analysis [17,18] of composites. However, due to the regular grid mesh used, non-orthogonal interfaces will appear stepped, or block-like in nature when the appropriate material properties are assigned to the voxel mesh. When considering the resulting stresses from mechanical loading, spurious stress concentrations will exist in the elements at the interface due to the stepped geometry, resulting in issues with stress continuity. These stress concentrations are highly localized and relatively benign for determining elastic stiffness of textile composites, but have a much higher risk of influencing predictions of failure and progressive damage analysis. Various smoothing algorithms for voxel mesh also have been developed [19,20]. Charras and Guldberg [21] used the boundary-specific filtering method to improve efficiently local solution accuracy of voxel-based model of complex biological structures, and found that the errors of filtered solutions consistently decreased after mesh refinement. Doitrand et al. [22] recently used a least squares method to interpolate the local non-smoothed voxel element stresses at surrounding integration points. However the interpolation process may remove realistic stress concentrations in elements situated in nearby regions. Thus, it was reported in Ref. [22] that this smoothing method may influence the predicted damage location. Thus it is necessary to overcome the problem of local stress concentrations if voxel-based meshes model of composites are to be used to analyze their mechanical behavior.

This paper describes a new, simple, direct and robust voxel FE method capable of obtaining accurate stresses at yarn interfaces in a voxel mesh, as well as correct progressive damage and failure analysis, for textile composites. A stress averaging technique is proposed to deal with the spurious stress concentrations arising. The effect of the local averaging domain size, averaging weight function and mesh dependence of the stress distribution is taken into account. A method for tracking the damage path is further developed to study the progressive damage propagation. A model of a single yarn embedded in a matrix with periodic boundary conditions and a transverse load applied is used as an example to examine the proposed method. The feasibility of the stress averaging technique to deal with composites with more realistic textile architectures is verified using a plain weave composite unit cell model.

2. Meshing issues associated with finite element models of composites

2.1. Artificial stress concentrations in voxel meshes

A representative volume element (RVE) containing a simplified circular cross-section inclusion with yarn properties, embedded in a matrix, is modeled as shown in Fig. 1 to demonstrate the issues that arise in voxel meshes. The longitudinal direction is aligned with the z axis, and the transverse directions with the x and y axes. The volume fraction of the yarn in the RVE is 60%. The yarn used in this model exhibits transversely isotropic homogeneous symmetry with characteristic effective properties of $E_z = 146.8$ GPa, $E_x = 11.4$ GPa, $\nu_{zx} = 0.3$, $\nu_{xy} = 0.4$ and $G_{zx} = 6.1$ GPa [23]. The properties of the isotropic matrix material surrounding with yarn are $E_m = 3.45$ GPa and $\nu_m = 0.35$ [24]. 8-noded solid elements (Abaqus/Standard element type C3D8R) are used to discretise the RVE and the enhanced hourglass control option is used to prevent spurious zero-energy deformation modes. Periodic boundary conditions are applied in both the longitudinal and transverse directions. Transverse compressive loading is applied in x direction.

In order to examine the spurious stresses generated in a voxel FE model, the RVE is discretised by voxel meshing with different mesh densities as shown in Fig. 2(a)–(c). A conformal mesh FE model was also created as shown in Fig. 2(d), to be used as a benchmark for verification. Fig. 2 shows the stress distribution in the loading direction for the models with different voxel mesh densities and the conformal mesh model. It can be seen that local stress concentrations appear at the stepped block-like interface between the yarn and matrix. This local stress concentration does not reduce with an increase in voxel mesh density. The minimum values obtained by the voxel mesh are notably lower than that of conformal mesh.

Fig. 3(a) and (b) shows the loading direction stress component for two paths, one along the yarn interface and the other across it. It can be seen that the stresses obtained from voxel meshes with

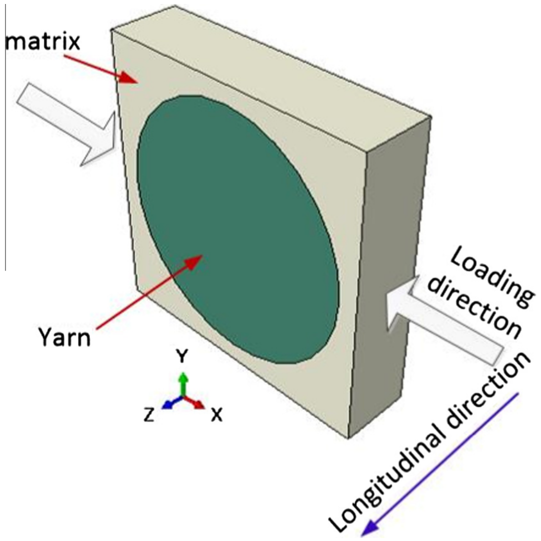

Fig. 1. Geometry of a single yarn embedded in matrix. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)