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Dynamic relaxation approach with periodic boundary conditions in determining the 3-D woven textile micro-geometry

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ABSTRACT

A dynamic digital element approach, utilizing a dynamic relaxation procedure, is developed to determine 3-D woven textile micro-geometries. Three yarn/tow structures, including plain yarn, twisted yarn, and twisted tow, are generated by the digital element mesh. An explicit algorithm with a periodic boundary condition is employed to calculate nodal forces, accelerations, velocities, and displacements within the unit cell. Because the majority of the computing time is consumed to detect contacts between fibers, an efficient contact search algorithm is proposed. In addition, a multi-level dynamic relaxation procedure is implemented to further reduce computer time. The yarn-level fabric micro-geometry is also generated in a format that can be read by commercial finite element software. The micro-geometries derived from numerical simulations are compared to the microscopic images of actual fabrics. Good agreement is found between numerical results and experimental results.

1. Introduction

The growth of textile composite applications drives the need for a more accurate mechanical property characterization of textile composites. Textile composite mechanical properties are determined by the internal geometry of the textile preform, which, in turn, is determined by the weaving process. Composite design requires not only a computer tool to link fabric performance to fabric micro-geometry, but also a computer tool to link fabric micro-geometry to the weaving pattern.

Fabric is woven from tows. A tow consists of a single yarn or multiple yarns and a yarn consists of many fibers. Fabric geometry can be observed and analyzed at the tow-, yarn- or fiber-level. At the tow- or yarn-level, micro-geometry is defined by both its axial path and its cross-section shape. At the fiber-level, yarn micro-geometry is defined by the axial path of each fiber in the yarn. The fiber's cross-section shape is assumed to be circular; however, the local yarn/tow cross-section shape is determined by fiber arrangement.

The 1990s saw the onset of the development of computer design tools for 3-D woven fabric geometric prediction. Verpoest et al. [1,2] developed a software package, named WiseTex. In their code, unit cell topology is defined based upon weaving pattern. Input yarn properties include yarn bending rigidity and yarn transverse compressive stiffness, both of which must be derived experimentally. Initially, yarn path is assumed to be a polynomial function. Yarn cross-section is assumed to be elliptical or lenticular. The polynomial coefficients and the ratio of the major axis length and minor axis length of the yarn cross-section are derived by minimizing the bending energy.

Robitaille et al. [3–5] developed a computer graphic software package, called TexGen, to generate fabric micro-geometry. It has gained wide usage in recent years because it is an open source code. Based upon microscopic observation or empirical procedure, yarn path key points are defined using a series of vectors from interlacing patterns. The cross-section shape along the yarn path can be assumed to be an ellipse, lenticile or polygon. Interpolation is performed to derive a detailed 3-D yarn shape. The 3-D fabric geometry generated by TexGen can be input into other commercial FEM software packages.

The major difficulty to use WiseTex is to define the input data, which include the yarn bending rigidity and the yarn transverse stiffness. Both play significant roles in the determination of the fabric micro-geometry, such as yarn cross-section shape and fabric thickness. TexGen is mostly a graphic computer tool. The user can conveniently input the fabric unit cell micro-geometry. The fabric micro-geometry must either be derived by microscopic observations or be based on assumptions.

Wang and her coworkers [6,7] originated a sub-yarn level micro-mechanics model, called the digital element approach (DEA), for textile fabric mechanics. Initially, the method was developed in order to determine the unit cell topology of 3-D braided fabrics. In a 3-D braided fabric, yarns orient in four different

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directions, so it is difficult to observe the unit cell topology based on microscopic imaging. In her method, each yarn is modeled as a rod element chain connected by frictionless pins. Yarn-to-yarn contacts are modeled by contact elements. A quasi-static numerical procedure based upon the DEA is used to simulate the 3-D braiding process step-by-step. As such, unit cell topology can be derived.

The DEA was later refined for the purpose of determining textile fabric micro-geometry at the sub-yarn level. In the newer version [7], a yarn is modeled as a bundle of digital fibers and each fiber is modeled as a rod-element chain. The yarn cross-section deforms due to the relative motion of fibers inside the yarn during the textile process. As such, both yarn paths and yarn cross-section shapes can be derived. This refined method was used to simulate the 2-D weaving process and the 3-D braiding process. Numerical results were compared to microscopic pictures [8] and they matched very well.

The major obstacle to use the refined DEA is the great computer resource required by the step-by-step quasi-static simulation of weaving or braiding processes. In order to resolve this issue, a relaxation procedure using static iteration was developed. In this procedure, the fabric topology is established based upon textile process kinematics. Then, a tension is applied to each yarn. Non-equilibrium nodal forces are calculated. A global stiffness matrix is assembled and nodal displacements are calculated. The static relaxation procedure requires less than 5% of the computer resource of that used by the step-by-step simulation of the textile process.

Based on a concept similar to the digital element, Madhadik and Hallett [9] discretized a fiber into many beam elements. The finite element software was used to analyze the micro-geometry of 3-D woven fabrics. Recently, Durrvile [10] discretized fibers into many finite strain beam elements. The approach was used to determine the micro-geometries of 2-D woven fabrics.

Fiber-level simulation can accurately predict yarn paths and yarn cross-section shapes inside the fabric. However, it requires much more computer resource. Even with the improved static relaxation approach, it often takes weeks to derive the micro-geometry of a 3-D fabric using a desktop PC with a multi-core processor. Therefore, development of a more efficient numerical procedure becomes a pressing issue.

In this paper, a more efficient dynamic relaxation procedure using DEA with a periodic boundary condition is developed. In the new procedure, the unit-cell topology is generated based upon weaving patterns. Yarn is discretized into multi-digital fibers. A periodic boundary zone is added around the boundary zone through a mapping process. An initial yarn tension is assumed. During the relaxation step, the non-equilibrium nodal forces inside the unit-cell are calculated first. Then, nodal accelerations, velocities, displacements and positions are calculated using an explicit process. Nodal positions inside the periodic boundary zone are updated through a mapping process. The simulation continues until all nodal forces are in equilibrium and all nodal velocities approach zero. Because the material domain includes only one unit-cell, computer requirements are significantly reduced. Computing time to derive a unit cell micro-geometry is reduced from roughly a week to hours. This approach has been used to determine micro-geometries of various 3-D woven fabrics. A software package, Digital Fabric Mechanics Analyzer (DFMA), has been developed [11]. One can derive both fiber level and yarn level micro-geometries of various 2-D and 3-D woven fabrics using a PC. The yarn level geometry can be processed for input to commercial FEM software, such as ANSYS, SolidWorks and MSC Marc [12].

2. Digital element approach and yarn structure

2.1. Basic concepts of the digital element approach

There are three key concepts in the digital element approach: digital fiber, digital yarn/tow, and contact element. As shown in Fig. 1, a digital fiber consists of many short rod elements, which are connected by nodes. For commonly encountered fabrics, yarns or fibers are so flexible that the effect of bending rigidity on the micro-geometry is negligible. As such, nodes connecting these rod-elements are modeled as frictionless pins which allow fibers to bend freely.

Digital fibers are bundled into a digital yarn. A digital yarn differs from an actual yarn and a digital fiber differs from an actual fiber. An actual yarn may consist of tens of thousands of fibers. The total number of digital fibers of a digital yarn is not determined by the total number of actual fibers in the actual yarn, but, rather, by the need to express a high quality yarn cross-section shape. A digital yarn usually consists of 10–100 digital fibers. In each simulation step, a contact search between digital fibers is conducted. A contact element is inserted once a contact is detected. Contact force is applied to corresponding nodes.

While a digital fiber is discretized into many short rods, modeled as truss elements that cannot be bent, we call this approach digital element analysis since the essential features of the analyses extend beyond the simple truss elements. In digital element analysis, the discretization includes two processes: yarn discretization and fiber discretization. In the yarn discretization, a yarn, which is a continuous domain, is physically split into many digital fibers. The transverse stiffness of a digital fiber differs from that of the corresponding yarn. Deformation of the yarn's cross-section is due primarily to change of the fiber's arrangement inside the yarn's cross-section, not from fiber cross-section deformation. The digital fiber is flexible because spherical joints connecting the rod elements allow bend both in- and out-of plane bending. The physics of the digital fiber, its flexibility, is not preserved by the truss element. It is achieved through the discretization process. Therefore, digital element discretization is a physical procedure and the truss elements are called digital elements. Accuracy of the results is determined by the resolution of the discretization. The resolution is defined by two parameters: the digital element length and the number of digital fibers per yarn.

2.2. Yarn/tow structure

There are two types of yarn micro-structures, plain and twisted. A tow consists of either a single yarn or multiple yarns. A multi-yarn tow is normally formed through a twisting process. Yarn/tow structure is created through the digital element meshing process in which each tow is split into yarn(s) and each yarn is split into multiple digital fibers.

If a plain yarn is discretized into multiple digital fibers, all fibers within the yarn are parallel to each other and are parallel to the original yarn's centroid path. If a twisted yarn is discretized, all fibers rotate along the original yarn path with a defined twist rate.

A procedure to determine the fiber paths within a yarn/tow is shown in Figs. 2 and 3.

In the first step of the procedure, the yarn/tow path is divided into iso-length segments connected by nodes as shown in Fig. 2. For simplicity, only four segments are shown in the picture. The yarn/tow path is represented by an approximate broken line $\overline{C_1C_2C_3C_4}$. S_1, S_2, S_3, and S_4 are yarn/tow cross-sections, which are perpendicular to the yarn/tow path. These cross-sections are initially assumed to be circular, deforming later during the relaxation