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Experimental and numerical investigation of the needling process for quartz fibers

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ABSTRACT

This paper investigates the deformation and damage of quartz preforms during the needling process. Effect of needling position and fabric thickness on the resistance force of the needle are experimentally researched. A numerical methodology based on the concept of virtual fibers is proposed to establish the geometry models of 2D broken twill and nonwoven fabrics. Then the needling process of the fabric plies is simulated by finite element method using an explicit dynamics algorithm. Deflection, stretch and breakage of the fibers are analyzed. The simulated fiber architectures of the needling positions are fairly close to the practical observations. Resistance force of the needling process can be predicted with satisfactory accuracy. The aim of the proposed approach is to generate the virtual fiber structure of needled preforms and obtain the effect of needling process on the fiber damage. This approach would be helpful for designing low-damage preforms and improve the mechanical properties of needled composites.

1. Introduction

Three dimensional (3D) needled preforms are manufactured from 2D woven and nonwoven fabrics [1,2]. Some in-plane fibers of the nonwoven fabrics can be transferred to the thickness direction (z direction) through needling (or needle-punching) process to enhance the bonding strength between the fibrous plies. 3D needling technology is more attractive than the traditional textile technologies, such as stitching, weaving, braiding and knitting for its simple manufacturing process and relatively low cost. Up to present, 3D needled preforms produced by quartz, carbon and even hybrid fibers have been used to manufacture high performance composites for aerospace applications.

Extensive observations [3–6] have been conducted to investigate the geometrical morphologies of the needled preforms. It was found that the fiber architectures of needled reinforcements are extremely complicated. Some nonwoven fibers were brought to the z direction. Breakage and deflection of woven fibers can be observed at the needling regions. What's more, the microstructures of needling regions show some uncertainty [7]. Fiber architectures of the preforms would affect the mechanical properties of composites significantly. At present, the damage of the fibers in the fabric plies during needling process cannot be quantitatively analyzed. 3D detailed geometry models of needled composites have not been constructed yet. A numerical framework which is able to predict the mechanical response of the fabrics in needling process would be a helpful tool to optimize the needling technology and improve the mechanical performance of needled preforms. Up to now, theoretical or numerical approach for analyzing the needling mechanism and for quantifying fabric damages has not been reported.

3D fiber architectures of fibrous composites can be characterized by the SEM [8] and Micro-CT [9,10] images. Then, the RVE [8,11,12] (representative volume element) models can be established in the yarn-scale [13]. The fiber structures of needled composites are difficult to be constructed explicitly in RVE models due to the complexity of the preforms. Some meso-scale models [7,14,15] were established to predict the effective stiffness properties of needled composites, in which the fiber architectures are simplified. These models are not suitable for damage analysis of the composites due to the lack of information regarding the detailed fiber structures. Micro-scale modeling methods (below yarn level) are needed to simulate the needling process and generate the fiber architectures of needled preforms.

Wang [16–18] proposed the digital-element model to simulate textile processes and generate the micro-geometry of textile fabrics. In this approach, the fiber yarn is digitized as an assembly of digital fibers and the digital fibers are modeled as the rod element chains. Digital-element model can be used for fabric deformation, strength and failure

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analysis in the sub-yarn scale (or near fiber-scale) [19–22]. Theoretically, each individual fiber should be represented by one digital-element chain to ensure the accuracy of the model. However, the number of fibers in a yarn is too large to simulate. It was found that 19–50 digital chains [17] would be sufficient to represent yarn cross-section geometry, and 70 chains [23] could model the tensile behavior of the yarn accurately. Song [24] generated the full-scale 3D geometric model of needled carbon fiber felt in the fiber-scale based on the statistics of the fiber length and curvature. Needling process of the fiber felt was simulated. However, stress-strain behavior of the fibers was supposed to be linear-elastic, and damage and breakage of fibers were not considered.

In this paper, the needling process for the quartz preforms composed of broken twill and nonwoven plies are investigated. Geometric models of the needled fabrics are generated using truss element-based virtual fibers in the near fiber-scale. Deflection, stretch and breakage of the fibers during needling process are analyzed. Resistance force (RF) of the fabric plies in the needling process can be predicted. 3D full scale geometry model of the needled preforms are reproduced. Needling experiments are performed to validate the simulated results. The simulation of needling process can be helpful for optimizing low-damage needling manufacture.

2. Materials and experiments

2.1. Materials

The quartz preforms under investigation are manufactured from broken twill and nonwoven fabrics using needling technology. The broken twill is a derivative weave structure for which the unit cell contains 4 warp (and weft) yarns, as shown in Fig. 2. The broken twill fabric under research is consist of 195 Tex warp and weft yarns. The nonwoven fabrics are manufactured from short-cut quartz fibers by the carding machine. The nonwoven fabric is highly porous and can be seen as a bird's nest shaped structure, in which the fibers distribute randomly. Structure parameters of the fabrics are listed in Table 1. In the needling process, the broken twill and nonwoven fabric plies are stacked up alternatively. Then the fabric plies are needled on the surface repeatedly, as shown in Fig. 1. With the needles penetrated into the plies, the broken twill yarns would be damaged, meanwhile some fibers in nonwoven plies are grabbed by the needle barbs and transferred to z direction to form the needling fiber bundles. Mechanical entanglements among the fibers are produced at the needling positions.

2.2. Needling experiments

The needling experiments are conducted on the Instron-8801 test machine and the 10 N static load cell was used in the tests. Rectangular specimens of 100 × 100 mm^2 are cut from the fabrics. The fabric specimens are placed between two cover frames which are bolted together, and the needle (needle code: 15 × 18 × 36 C333) is fixed in the upper clamp as seen in Fig. 2. Five groups of specimens are needled, as listed in Table 2. The hybrid ply is composed of 1 nonwoven ply and 1 broken twill ply (with the nonwoven ply placed on the upper position). Before the needling tests, the edge regions of single-ply specimens (groups A and B) were embedded in epoxy, while edge regions of multi-ply specimens (groups C, D and E) were needled together in order to avoid the unravelling of fibers from the fabrics. Punching in and pulling out of the needle are carried out under stroke control at the cross head speed of 20 mm/min. The needling depth is 20 mm. Resistance force (RF) and needling depth (ND) of the needle are recorded continuously in the tests.

Table 1
Geometric and mechanical parameters of the materials.

Parameters		Values
Broken twill	Yarn spacing L	1.66 mm
	Yarn width W	1.0 mm
	Yarn height H	0.3 mm
Nonwoven fabric	Length of the fibers L_f	50–80 mm
	Areal density d	60–80 g/m^2
	Thickness T	0.5 mm
Quartz fiber	E-modulus E	78 GPa
	Tensile strength σ_t	6 GPa

3. Numerical simulation approach using digital element method

3.1. Geometry modeling

3D fiber structures of the broken twill and nonwoven fabrics are reproduced by virtual fibers. The virtual fiber is constructed by digital elements, i.e., a chain of truss elements, by Abaqus software. The truss element-based virtual fiber has essentially no bending stiffness. Nevertheless, individual virtual fibers cannot bend freely due to the contact and friction constraints of the neighboring fibers. Any displacement perpendicular to the fiber direction would result in the opposing force along fiber direction. Therefore, the virtual fibers can also provide the flexural rigidity.

For broken twill fabric, each yarn is represented by a bundle of virtual fibers. Initial cross-section of warp/weft yarn is supposed to be ellipse. Spacing between yarns and the dimensions of yarn section are determined from the micro-observations (as listed in Table 1). Spatial path of the yarn at weave points can be described by a sine function, written as Eq. (1).

$$z = \pm H \sin\left[\frac{\pi}{L}\left(x - \frac{L}{2}\right)\right] \tag{1}$$

The yarns have been twisted before the weaving procedure. But the twist was relatively low (only 5 twist/10 cm). The twist of the yarns would also release at some level after the fabric was cut into the 100 mm × 100 mm specimens. In the virtual fiber models the twist of the yarns were not considered for simplicity. And the fibers were perfectly aligned along the yarn path (see in Fig. 3).

Geometry model of the nonwoven fabric is constructed by two steps, as shown in Fig. 4. Firstly, virtual fibers were generated and assembled in a region sized 65×65×30 mm^3. The length, orientation and curvature of virtual fibers were determined by the statistics of nonwoven fabric specimens. Avoidance of fiber interpenetration is achieved using the algorithm reported by Song [24]. Secondly, the highly loose nonwoven fiber structure is compressed by applying gravity to the virtual fibers until a certain thickness is achieved. An explicit dynamic algorithm was used to simulate the compression process of the nonwoven fabrics. Contact between virtual fibers were established using Abaqus' general contact algorithm. During the compression step, the movement of the nonwoven fiber ends in x and y directions were constrained to zero. After the compression process, the virtual fibers would be still in the region sized of 65 × 65 mm^2. Virtual nonwoven fabrics with arbitrary areal density can be obtained by changing the amount of virtual fibers.

3.2. Numerical analysis and model parameters

An explicit dynamic algorithm was employed to simulate the needling process of the fabric plies. Two steps (Dynamic, Explicit) were created to simulate the punching in and pulling out procedures. In accordance with the experiments, displacements of fiber ends for both woven and nonwoven fabrics along x, y and z directions were constrained to zero, as shown in Fig. 7(a) and Fig. 8(a). Displacement boundary conditions z = −20 mm and z = 20 mm were applied to the needle in step-1 and step-2 respectively. To achieve an economical