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Generating virtual specimens for complex non-periodic woven structures by converting machine instructions into topological ordering rules

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ABSTRACT

We describe the generation of geometrical models of complex, non-periodic, three-dimensional (3D) textile structures, which combine reinforcing tows and open spaces formed by the use of fugitive tows or alloy rods. Modeling begins with the machine instructions that are executed on the weaving loom to create a 3D textile architecture, including instructions for unusual machine operations that create functional features such as holes or joints. Data include only simple specifications of the nature of each tow, such as its cross-sectional area and approximate stiffness. The weave architecture is defined by sets of bounded integers, an ideal input data structure for computational design optimization. Models are generated automatically via simple algorithms based on topological ordering rules. Diverse outcomes are illustrated by a sandwich structure and a cooled airfoil component. The generation of complex structures that are built from very many machine instructions is simplified by identifying “design instructions”, which consist of repeated patterns of machine instructions that can be entered into the input deck very quickly, rather than by entering each machine instruction separately. Yet symmetry, including periodicity, is not necessarily present: the airfoil exemplar demonstrates the use of design instructions to form an asymmetric structure along whose length the number of tows and their interlacing pattern both vary.

1. Introduction

1.1. Virtual tests using large-scale virtual specimens

The idea that a virtual test can function as a tool for optimizing material design has inspired a generation of engineering scientists [1]. A virtual test can yield rich information about the correlation between the microstructure of a material and its performance, because in a virtual test, in contrast to a real test, we have full knowledge of the microstructure and its effect on the details of failure mechanisms.

Prior developments of virtual tests have focused primarily on relatively small scales in materials, such as the grain size in an alloy [2–4], the fiber scale and the unit-cell scale in a composite [5–10], and the atomic scale, e.g., in studying interfaces and multi-functional materials [11].

In this work, we pursue the generation of virtual specimens for textile-reinforced structures that have the size of a sub-component and are therefore much larger than the tow (or fiber bundle) size. At the sub-component scale, one requires, for example, to match the reinforcement design to the load-paths in the sub-component, which are complicated by part geometry and non-uniform loading. Of particular interest in this article is the association of architectural outcomes in the textile reinforcement with machine operations executed on the weaving apparatus on which the textile fabric was formed. Analyzing the relation of architecture to machine operations is the first step towards creating a virtual test optimization tool for the reinforcement architecture. Completion of the tool by predicting performance and iterating over architectural design choices remains for the future.

1.2. Integral textile structures

The structures of present interest are “integral textile structures” [12,13], which share the following characteristics:

1. Reinforcing tows are arranged in complex 3D patterns that ideally present fibers parallel to any significant load path, either in-plane or out-of-plane, at any point in the structure.

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2. The geometry of both the exterior surface of the structure and of internal features such as holes or cavities is formed to near-final shape without needing to cut any reinforcing fibers; i.e., the fiber tow architecture creates the external and internal shapes as inherent characteristics of the weave.

Because the required geometry of the structure is generally complex, and the thermal and mechanical loads it sustains are generally non-uniform, the optimal reinforcement architecture is also generally complex; in fact, its complexity must match that of the structural geometry and the expected spatial variations in loads. In particular, the reinforcement architecture is generally aperiodic, showing local variations that are specific to particular structural features. Therefore, accurate analysis of the performance of a candidate reinforcement architecture generally requires that the entire structure be generated as a virtual specimen and analysed *in toto* without homogenizing the reinforcement architecture.

While the rewards of integral textile structures are clearly indicated by successful prototypes [12], we will demonstrate below that dealing with their inherent complexity presents some interesting challenges in physical representation and numerical methods.

1.3. Topology-based approaches to simulating textile preforms

Any textile can be regarded as an interlaced assembly of tows (fiber bundles). The pattern of the interlacing can be expressed as a set of ordering relations among the tows, e.g., which tow passes above or below another, or to its right, or to its left. The set of ordering relations is unique to a textile type (plain weave, satin weave, interlock weave, etc.); in fact, it defines the textile type [14,15]. The set of orderings defines the topology of the textile, but not its geometry: thicker tows woven in a plain weave and thinner tows woven in a plain weave both yield plain weave topology, with identical ordering relations, but the thicker and thinner tows will certainly yield fabrics with differing geometrical dimensions. Furthermore, when a fabric is draped, its geometry changes in a complex manner, yet its topology remains unaltered. The topology of a textile made of continuous tows can only be altered if tows are cut.

The topology of a textile is established on a textile machine, such as a weaving loom or braider. The topology is established when the machine executes certain actions, such as the raising or lowering of one set of tows in a loom before a second set of tows is inserted, or the rotation around each other of the bobbins that supply tows in a braider. When the machine executes such actions, it follows machine instructions, which in a modern machine are computerized codes that direct the machine to create a specific textile architecture (topological outcome).

The relationship between machine instructions executed on weaving looms and computer science is very old [16]; but the development of computer algorithms to model the textile structures that are implied by a given set of machine instructions remains an evolving topic of research (e.g., [17,18]). Pertinent forerunners to the methods followed in this paper are due to Lomov and colleagues [19–21], Verpoest and Lomov [22], and Brown and colleagues [23]. The algorithms presented here offer generalizations that allow aperiodic structures with complex geometry to be generated, a pre-requisite of the engineering concept of integral textile structures.

2. The representation of loom operations as a set of machine instructions

We consider a loom in which generally parallel warp tows are interlaced with generally parallel weft tows and the warp and weft tows are generally mutually orthogonal. A representative sketch of the configuration of tows and of those active components of the loom that enter into the description of the model is shown in Fig. 1.

We demonstrate that complex architectures with diverse character can be generated using a common form of input data deck, which comprises the topological data that define the interlacing patterns of tows together with minimal geometrical and mechanical data for the different tow types that may be present. The input decks are constructed as spreadsheets. Complete input decks for two illustrative cases, one a sandwich structure and the other an airfoil, can be found in Supplementary Material published online. The input deck for the sandwich structure, "*input deck sandwich*", is the smaller deck. The reader may find it helpful to refer to it while working through the following details.

2.1. Types of tows

Individual warp and weft tows may be of different type. The input deck contains a list of candidate tow types, which may used as any weft or warp tow. For each tow type, denoted T, the following set of characteristics is explicitly listed in the input deck.

(i) The retention flag, $R \in \{\text{True, False}\}$, which specifies whether the tow will remain as part of the structure of the fabric ($R = \text{True}$) or whether it is a sacrificial tow, which will be removed from the product at some time ($R = \text{False}$).
(ii) stiffness/tension parameter, denoted k, which takes one of three values: $k \in \{0, 1, \infty\}$.
(iii) The area and aspect ratio of the tow's cross-section, denoted A and AR, whose specification is equivalent to specifying the denier or fiber count of the tow and the degree to which it is flattened into a ribbon-like entity when it is fixed within the weave.

Thus a tow type is specified by the set of data

$$T = \{R, k, A, AR\} \tag{1}$$

Tows that will be retained in the fabric ($R = \text{True}$) may have any value of the stiffness parameter k. Retained tows with $k = 1$ are usually fibrous tows that serve as primary reinforcement. Retained tows with $k = 0$ are fibrous tows that are intended to deform easily around other tows, e.g., light threads used in weaving a "uniweave" fabric, which is a fabric of nominally straight and parallel reinforcing tows that are held in place by light tows that move around them without displacing them. Retained tows with $k = \infty$ are usually metallic rods, which are used, e.g., in integrally woven textile components as anchors onto which an external metallic structure may be joined [12].

Tows that will not be retained in the fabric ($R = \text{False}$), which are also termed "sacrificial tows", are used to introduce space within a fabric. Like a retained tow, a sacrificial tow may have any stiffness: it may be rigid metallic tooling ($k = \infty$), in which case reinforcing fibrous tows will displace around it; or it may itself be a fibrous tow ($k = 1$ or $k = 0$), in which case it may be made to follow curved paths through the fabric, a technique used, e.g., to introduce large area densities of small cooling ducts that pass through the skin of a heat exchanger [12].

Tows with stiffness $k = \infty$, e.g., metallic tooling tows or structural rods, can in principle be inserted either as a type of warp tow or a type of weft tow. Insertion of tooling or structural rods as weft is straightforward, whereas insertion as warp is complicated by the presence of the reed and the beat-up action (Fig. 1), but, for maximum generality, we consider both possibilities, assuming ingenious loom operators.

While only two shape characteristics, A and AR, need be defined as input for the generator, other features of the cross-sectional shape can be developed in subsequent modeling steps that build