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Confluent 3D-assembly of fibrous structures

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ABSTRACT

The ability to independently control fiber alignments and structural geometry is critical for design of optimal three-dimensional (3D) fibrous structures. We present a novel method to 3D-assemble carbon fiber structures, containing no seams or adhesive joints, using a confluence of several textile methodologies. A variety of complex structural shapes with tailored fiber topologies are demonstrated to be achievable. These optimized structures are shown to have unprecedented static and dynamic strength as well as damage tolerance and ductility. For example, the energy absorption capacity of a 3D-assembled carbon fiber prismatic sandwich structure is shown to be 300% greater than a high performance metallic counterpart.

1. Introduction

Tailoring the alignment of fibers in a composite material or structure is crucial for maximizing properties like high strength, stiffness, fracture toughness and damage resilience [1]. Fiber alignment in natural structures often varies with the position to meet local functional objectives [2]. The rachis (shaft) of a bird feather, which is considered to be a highly efficient naturally occurring fibrous structure, can diagrammatically be treated as a beam with webs and faces [3]. The web of the rachis is a layered composite with a ±45° fiber alignment so as to resist shear forces. It is connected to the faces via a three-dimensional (3D) fiber alignment that ensures that the joints have a high toughness and ductility [3,4]. Although nature shows many other examples of structures where fiber alignment is analogously optimized, synthetic production of composite structures where fiber alignment and structural topology can be independently tailored in 3D has proved elusive [1].

There are a range of well-established methods to produce two-dimensional (2D) arrangements of reinforcement, e.g. textile technologies using high performance fibers such as carbon fibers [5]. However, structures with a 3D fiber topology are desired due to their superior multi-axial performance [1]. Efforts have been made to modify 2D textile technologies to produce complex 3D shapes using generally so-called 3D-weaving. These have shown promise but are unable decouple macroscopic structural topology and microscopic tow/fiber alignments [6–8]. Most of these 3D solutions are based on the principle of adding out-of-plane reinforcements to a planar 2D weave, examples include z-pinning [9,10], interlock-weaving [11] and stitching [12,13]. Well-established 3D textile methods such as braiding [14,15] and knitting [16] have also been demonstrated to directly produce near net-shape structures. However, in braiding and knitting the structural geometry and fiber alignments are inherently interlinked, and structures produced by these methods are often sub-optimal. Here, a new method to 3D-assemble continuous long fibers is described that enables independent control over structural geometry and fiber alignment. We can thereby synthetically produce optimal geometries and fiber arrangements for a given function. The method is a confluence of different textile technologies such as weaving and braiding. The innovation lies in circumventing the inherent (physical/geometrical) limitations of the conventional weaving principles [17] in order to realize 3D-assembly of structures.

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2. Materials and manufacturing

The process to manufacture 3D-assembled carbon fiber structures is briefly described here. It is instructive to compare the performance of the 3D-assembled structure with state-of-the-art material systems currently used in aerospace and marine structures. For this we choose the following two benchmarks: (a) an equal mass and same overall geometry aerospace grade 6061-T6 aluminum alloy beam (denoted 6061-T6) and (b) an equal weight and volume carbon fiber reinforced epoxy (denoted CFRP) sandwich beam with a high performance polymer foam core.

2.1. 3D-assembly of carbon fiber structures

The 3D-assembled composite beams were manufactured in two steps. First, a dry preform was created using the confluent 3D-assembly process with carbon fiber yarns and then the preform was infused with a polymeric resin using a rigid tool to ensure that the dry preform retained its geometry and fiber alignment under the infusion process. The final *as infused* 3D-assembled composite beam had an overall geometry and dimensions as depicted in Fig. 1.

2.1.1. High-level description of the confluent 3D-assembly process

The technology for confluent 3D-assembly and the preforms used in this study were supplied by the textile company Biteam AB.[1] We here provide a high-level overview of the process to highlight the key innovations of the process. The confluent 3D-assembly process involves three innovations to augment the traditional weaving process. First the so-called warp fiber tows are brought in perpendicular to the plane of the weave and the so-called weft tows are inserted at the bend of the warp tows as shown in Fig. 2a to form a 2D-weave. Moreover, the warp tows are brought in at multiple positions along the assembly line in order to produce a multi-layer weave in a single step, see Fig. 2a. In traditional weaving the warp tows are fed in the plane of the weave which physically prevents the single-step production of multi-layer weaves. Another drawback of the in-plane warp tow feed is that the feeding machinery occupies space at the inlet of the weave. Since the warp feed machinery in this new process is located above/below the weave we have now opened the possibility to add fabrics that are fed at the inlet of the weave at arbitrary orientations; see Fig. 2b. These “add-on fabrics” can have any desired fiber alignment (Fig. 2b shows a ±45° configuration) and can be produced using a variety of textile techniques (e.g. flat braiding) that are fed into the assembly line. This is the second innovation. The final innovation is that these “add-on fabrics” are interlocked with the weaves via the weft tow insertions as shown in Fig. 2. The tow wavelengths of the weaves and add-on fabrics can be tailored to achieve the desired degree of interlocking. In Fig. 2c an example is shown where the weave and add-on fabric have equal tow wavelengths, which results in a fully interlocked structure. The method is thus a confluence of a range of textile processes which results in 3D interlocked achitectured structures. The method to 3D-assemble architectured structures with webs and faces, inspired the development of a prismatic beam similar to the highly efficient bird feather rachis as shown schematically in Fig. 2d. The 3D-assembled structure comprises two webs that are inclined at approximately 50° to the faces to create high torsional stiffness and provide lateral stability to the beam. The webs are designed to comprise six laminae, each laminae having a fiber alignment of ±45° with respect to the beam longitudinal direction. Moreover, the joints of the webs to the faces have a fully interlocked 3D fiber arrangement (Fig. 2c) which maximizes toughness of the joints that are typically the weak links in traditional composite structures. An optical photograph and an *X*-ray computed tomography (*X*-CT) of the 3D-assembled beam

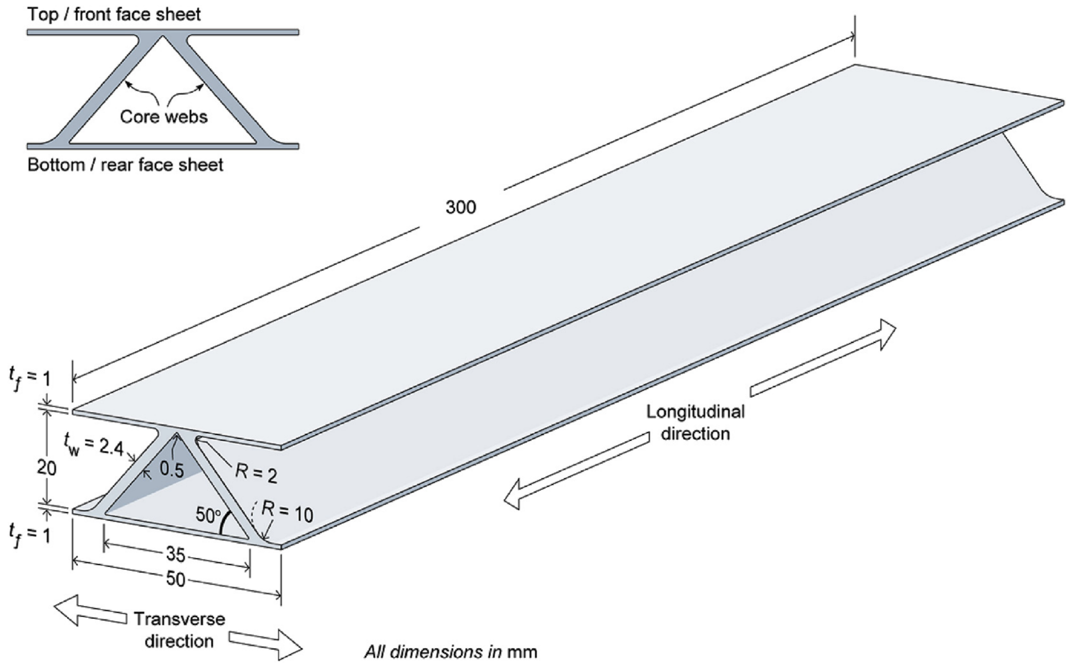

Fig. 1. Sketch showing the overall geometry of the 3D-assembled bird feather rachis-like beam. The naming conventions for the different parts and directions of the beam are also indicated.

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[1] Biteam AB, Bromma, Sweden. http://www.biteam.com.