NEW FRONTIERS FOR TEXTILE STRUCTURAL COMPOSITES

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1. Introduction

There is a global renewal of interest in manufacturing technology for lightweight materials, with a major focus on automotive composites. This is evident in the national initiatives embarked in recent years, notably the Institute for Advanced Composites Manufacturing Innovation (IACMI) led by the University of Tennessee in the USA; the Institute for Carbon Composites in Germany (LCC); and the National Composite Center led by Nagoya University in Japan. It is of interest to note that carbon fibres and textile structural composites (TSC) are the key focuses in these manufacturing initiatives.

TSCs are composite materials reinforced by textile structures for primary structural applications. Although textile structures have long been used for composite reinforcement, serious use of textiles for structural composites did not occur until the entering of the space age with the development of carbon fibres and multiaxial 3D textile preforms. The need for affordable composites that have significantly improved the through-the-thickness strength and damage tolerance intensified the development of a wide variety of textile preforms, which established the foundation for the use of textile composites for aircraft primary structures as shown in Figure 1.

Because of its impact on energy consumption and environment automotive application is expected to be the next major growth area for carbon fibres. Figure 2 illustrates the intensive use of TSC for electric vehicles [Ko]. The rapid advancement of electronics and nanotechnology will transform carbon fibers from mainly a structural reinforcement material to multifunctional smart material capable of not only reinforcing but also sensing and communicating functions. These functions will be delivered through fiber architecture design at fiber (nano and micro), linear fiber assembly (yarn), and fabric (2-D and 3-D) levels.

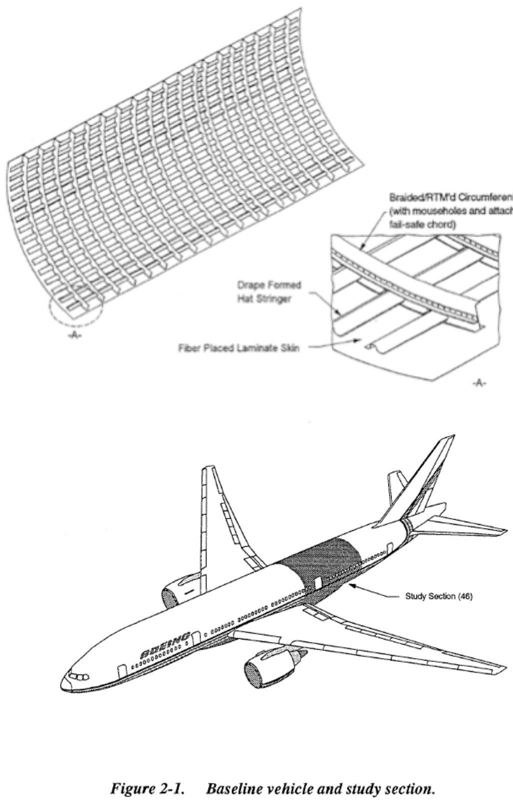


Figure 1: Textile composite for aircraft applications [1]

In this presentation, after a review of the unique characteristics of TSCs and their advanced applications, we will discuss the lessons learned in the development of TSCs. This will be followed by an introduction to the current approaches to significantly reduce the cost of carbon fiber through the development of low cost renewable carbon fiber precursors. We will conclude by examination of future opportunities for TSC in vehicle and human health monitoring using multifunctional composite nanofibres.

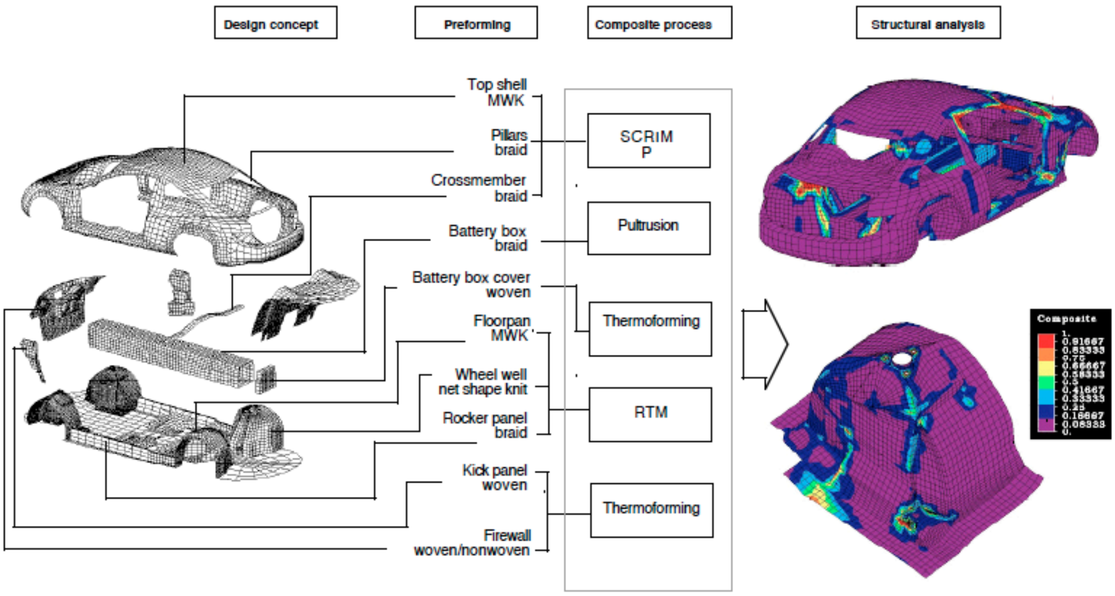


Figure 2: Textile composites for automotive applications. [2]

2. Low-Cost Carbon Fiber from Renewable Resources

Carbon fibers can be produced from different precursors, such as polyacrylonitrile (PAN)[3-5], pitch[6-8], cellulose (rayon) [9-11], polyvinylchloride(PVC)[12-14], polyethylene[15, 16], poly(vinyl alcohol) (PVA)[17, 18], poly(vinylidene fluoride) (PVDF)[19] and lignin[20, 21]. The key obstacle to the entry of carbon fiber into the auto composite market is the high cost of PAN based carbon fiber. Current price of carbon fiber is over US$30/kg, while the automotive industry requires carbon fiber cost less than $11–$15.40/kg with a tensile strength of 1.72 GPa (250 ksi; 176 kg-f/mm^2) and a modulus of 172 GPa (25 Msi; 17.6 × 103 kg-f/mm^2) [22]. Therefore the cost of carbon fiber must be significantly reduced for it to be feasible for wider utilization.

Lignin is nature's most abundant source of aromatic compounds, and represents 30% of all non-fossil organic carbon on Earth. In addition to lignin being a renewable and low-cost feedstock material, it is also a highly oxidized molecule that readily undergoes fiber crosslinking under thermal treatment. In fact the thermal stabilization process for lignin-based fibers requires shorter stabilization times and lower stabilization temperatures than PAN fibers, which means lower processing costs [23-25]. Therefore, of the large number of potential lignin-based products carbon fiber has been identified as one of the highest value adding options for lignin. The U.S. Department of Energy (DOE) estimated that the potential cost of lignin based carbon may be reduced to around $4/kg providing a manufacturing cost of $6.27/kg with a carbon yield of 55%[26]. Therefore, substituting PAN with low cost lignin as the renewable carbon fiber precursor is both economically and environmentally attractive. The level of interest in lignin-based carbon fibers can be seen in some recent government and industry programs [22]. For example, in 2011, the US Department of Energy (DOE) awarded Zoltek Inc. a project entitled "Development and Commercialization of a Novel Low Cost Carbon fiber". Zoltek, then collaborated with Weyerhaeuser to produce carbon fibers by partial substitution of PAN with lignin using the wet spinning method. The Zoltek-Weyerhaeuser team succeeded in producing pilot-scale carbon fibers containing up to 45 wt % lignin.

3. Multifunctional Composite Carbon Nanofiber

Structural health monitoring (SHM) aims to give, at every moment during the life of a structure, a diagnosis of the "state" of the constituent materials, of the different parts, and of the full assembly of these parts constituting the structure as a whole [27]. It involves the integration of sensors, possibly smart materials, data transmission, computational power, and processing ability inside the structures. By integrating of smart or intelligent materials and structures for SHM, vehicles will become more reliable and require less operational and maintenance cost (Figure 3). Responding to the need for SHM. UBC developed the enabling materials for sensor/actuators by multiscale integration of these functional. nanomaterials (nanoparticles, nanotubes, nanowires, and graphene) in the form of fibers, linear fiber assemblies, fabrics, and composite structures while utilizing conventional carbon fiber as a structural backbone for the next generation of fly-by-feel autonomous vehicles. Table 1 summarized the concept, process, and applications of these integrated nanofiber composites.

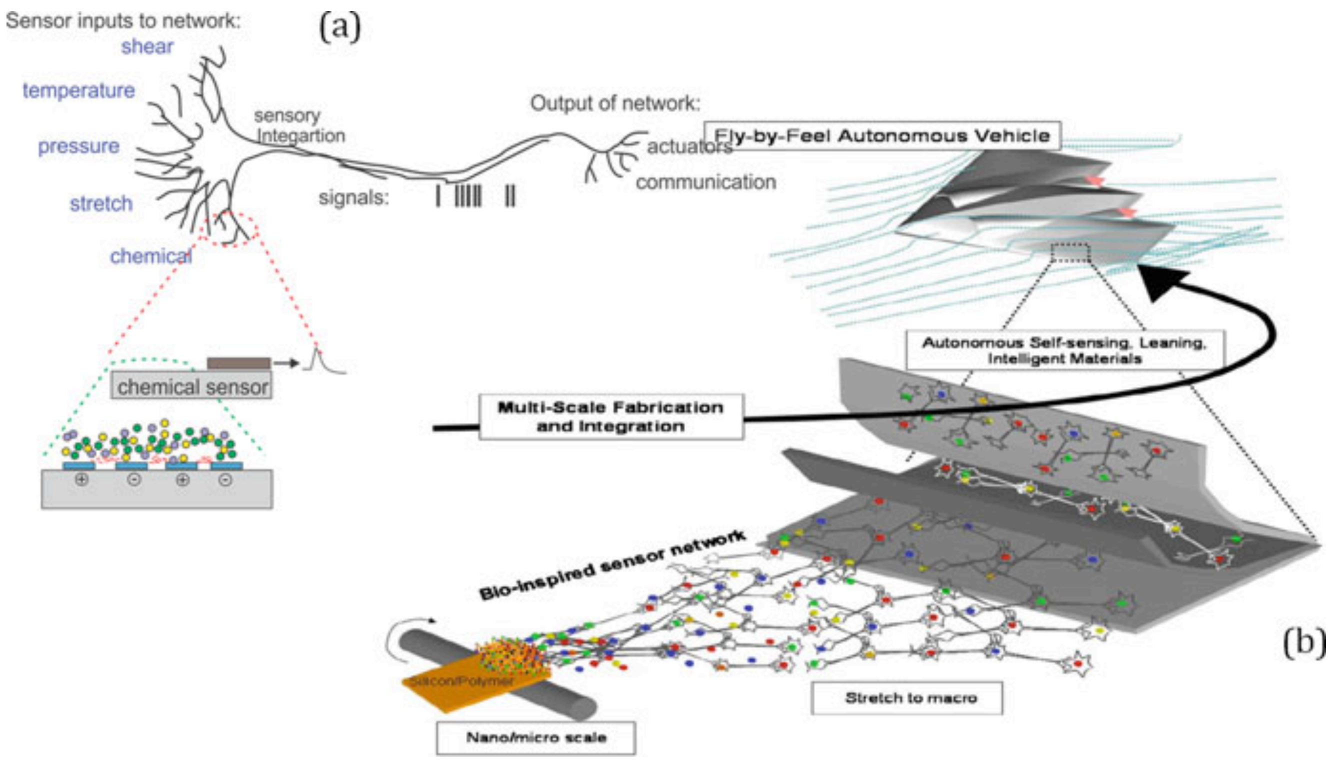
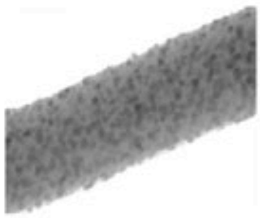
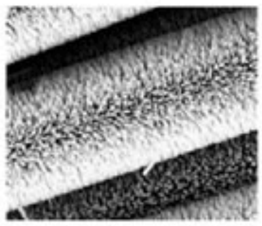
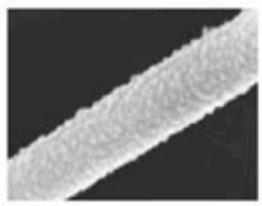


Figure 3: Nanofiber sensors for fly-by-feel autonomous vehicles

Table 1. Concepts, processing methods, and exemplary applications of multifunction nanocomposite fibe

Concept			
Electron Microscopic image			
Process	Nanofiller encapsulation	Nanowire growth	Nanoparticle surface coating
Application	EMI shields Structure reinforcement	Stress sensor Power generator	Stress sensor Chemical sensor Catalyst

4. Advanced Fiber Placement Technologies

4.1 Hexagonal 3D Braiding Technology

With the objective to reduce the machine to part footprint ratio and increase the yarn packing density hexagonal braiding is a new braiding mechanism developed by the Ko group to fabricate complex shaped 2-D and 3-D composite structures.[28] The realization of hexagonal packing is based on the arrangement of three circles, wherein the center points are each equal to a corner of an equilateral triangle and they have a common point of intersection in the balance point of this triangle. The unit formed by this arrangement is shown in Fig4 (a). Joining six of these single units together to form a hexagon thus creating hexagonal packing of seven circles, referring to as the basic unit, as shown in Figure 4 (b). The footprint of the mechanical realization of this packing is illustrated in Figure 4 (c). This unique cam arrangement allows every cam to carry a maximum number of six carriers placed in sixty-degree intervals around the cam, though only one carrier is allowed to take a mutual position between two adjacent cams, and therefore six different directions of planar carrier movement. Compared to traditional four bobbin carriers that are capable of moving carriers in four different planar directions this unique hexagonal cam arrangement adds two more planar movement directions to the process.

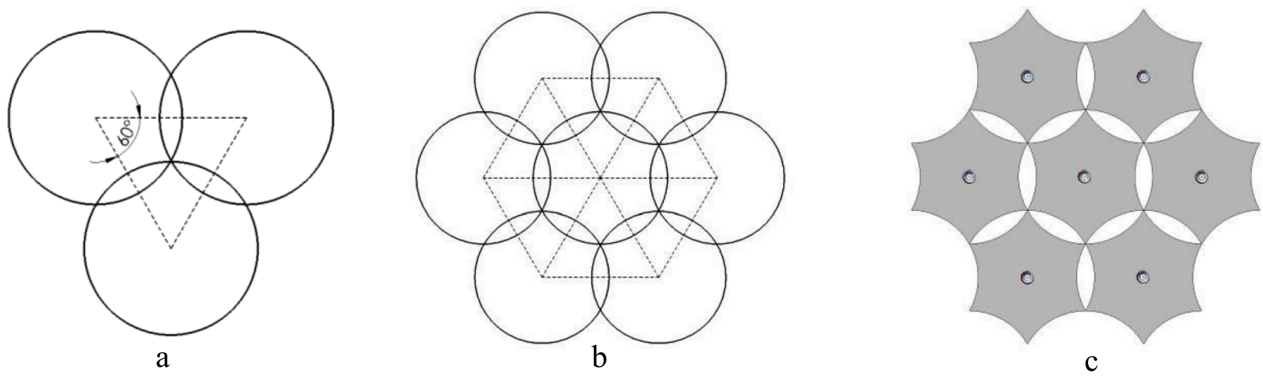


Figure 4: Hexagonal braiding unit[28]. (a) single unit, (b) basic unit and (c) hexagonal cam packing

4.2 3D Printing of textile Structures

3D printing, also known as additive manufacturing (AM), has gained popularity recently as a prototyping technology. Differencing from 2D printing, 3D printing prints out 3D objects by the repetitive addition of thin layers. 3D printing technology has found applications in various industries such as architecture, airline, medical[29, 30], electronics and even food industry. For its quick forming and versatility, 3D printing or additive manufacturing is regarded as a 'revolution' of the 2010s for production. McKinsey GLOBAL Institute research suggests that 3D printing could have an annual economic impact of $550 billion by 2025. Recognizing the quick turn around in prototyping, the textile industry has utilized 3D printing mainly for fashion design.

For example weft-knitted structures and lace patterns have been produced by selective laser sintering (SLS) and fused deposition modeling (FDM) printing methods[31]. The printed weft-knitted structures were produced in larger size than traditional knitted fabrics to obtain a thickness that holds the structure in one piece, as shown in Figure 5. Beecroft[32] demonstrated the possibility of using of Nylon powder to print both flexible single knit (single-faced) and double knit (double-faced weft knitted structures,) which make them viable solutions for use in the technical textile industry.

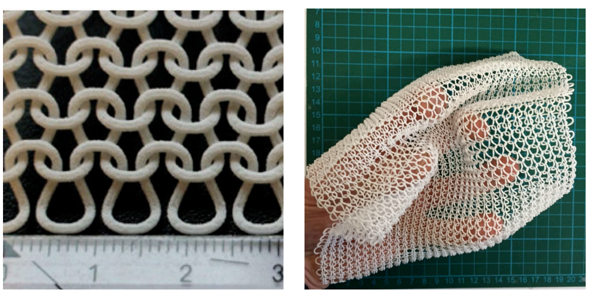


Figure 5 SLS printing weft-knitted structures produced by Melnikova et al.[31] (left), and produced by Beecroft [32] (right) respectively.

3D printing technology almost completely abandoned the traditional clothing production method[33]. First of all, 3D printing deposits a filament directly into a 3D structure with the pursuit of fitness through the accurate modeling of computer. Secondly, 3D printing structure can achieve a wide variety of complex styles that traditional textile industry cannot express through computer designing. However 3D printing textile structures tend to lack flexibility and softness due to the abandon of the fiber and yarn spinning processes. Innovative improvements are needed to make it a faster and more versatile method to produce flexible textile materials. However it has been found that 3D printing is a valuable tool to study 3D fiber architecture.[34,35,36]

Due to the complexity of 3D braiding structure, structural and mechanical analysis of 3D braided preforms are challenging, especially for the case of the newly developed hexagonal braiding. So far, the basic unit cell of hexagonal braiding has not been fully identified. The prototyping advantage of 3D printing makes it possible. By tracking the cam travelling history, the yarn paths can be established, 3D modeled therefore a 3D braiding structure can be printed out for analysis. Chou's group[34, 35] explored 3D printing multi-directional composite preforms such as 2D woven preforms, 3D woven preforms, honeycomb preform, z-pinned sandwich preform and 3D braiding preforms. Figure 6 shows the 3D printed 3D braiding structure. This exercise highlighted the aspects of AM critical to composite and general materials processing and demonstrated

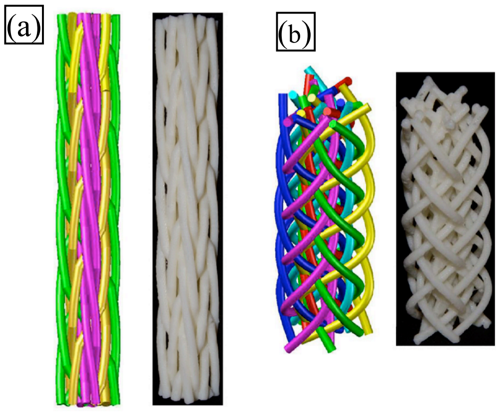


Figure 6: Braiding model (left) and printed braiding preforms. (a) 3D rectangular 4-step braided preform, and (b) 3D cylindrical 4-step braided preform.

the high fidelity between modeled and additively manufactured structures within the scope of composites. Similarly, 3D printing can also be utilized for evaluation of the microstructural features of complex 3D structures. By conducting compression tests on 3D printing orthogonal and braided preforms fused with silicone matrix, Chou et al.[36] demonstrated the feasibility of investigating the microstructural features and damage evolution of multi-directional preforms and composites with the aid of AM technique.

5. Conclusions

Textile structural composites are expected to play an important role in the growth of the next generation of lightweight fuel-efficient vehicles. In order to realize the opportunities in automotive composites we must address the need for low cost carbon fibers from renewable sources. There is increasing needs for multifunctional fibers and fibrous structures (e-textiles) as the smartness of automobile increases. Advanced manufacturing of textile preform will continue to evolve, capable of constructing complex 3D fiber architecture benefiting from the rapidly advancing 3D printing technology.

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