A Review of Preforms for the Composites Industry

P. M. Wambua* and **R. Anandjiwala**
CSIR Materials Science and Manufacturing, Fibres and Textiles Competence Area, P.O. Box 1124, Port Elizabeth 6000, South Africa

ABSTRACT: Preforming technology has emerged as core to the manufacture of engineering composites with enhanced properties at reduced production costs. Textile technologies such as weaving, knitting, braiding, stitching and nonwoven individually or in combination have been utilized in the design and manufacture of 1D, 2D, and 3D preforms boasting increasingly complex architectures. Current research appears to be geared towards reducing the occurrence of delamination as well as improving out-of-plane impact properties by through-the-thickness reinforcement. Utilization of improved impregnation techniques has played a vital role in the processing of preforms for the aerospace, automotive, marine and other advanced engineering applications. The current and previous research on preforms as well as the techniques used in their manufacture has been reviewed in this article and future emerging trends highlighted.

KEY WORDS: preforms, composites, composites industry, multidirectional, applications.

INTRODUCTION

PLENTY OF RESEARCH on preforms for composites has been reported in the literature. The areas so far addressed by various researchers include, but not limited to, mechanical properties [1,2], performance [3], draping [4] and permeability [5,6]. A preform may be defined as a specific assemblage of unconsolidated (i.e., no matrix added) fibrous materials such as fibers, yarns and fabrics. High modulus fibers such as carbon and glass are often used to

---

*Author to whom correspondence should be addressed.
E-mail: paulwambua@yahoo.com
Figures 2 and 5 appear in color online: http://jit.sagepub.com

1528-0837/11/04 0310–24 $10.00/0 DOI: 10.1177/1528083709092014

make up textile preforms, which are subsequently cured or consolidated to form structural components [7]. Textile fabrics, utilizing technologies such as weaving, braiding, or knitting have consolidated their place as important preforms for advanced composites manufacture. A textile preform ensures better control of fiber displacement as well as ease of handling and transportation, thus reducing labor costs and increasing production rates in composites manufacture [8].

Due to the different manufacturing processes, textile preforms vary considerably not only in terms of fiber orientation and the degree of entanglement, but also in the geometry. The preform architecture (varying from simple unidirectional yarns to complex 3D preforms) is of great importance because it influences the properties and performance as well as the cost of the composites. The ever increasing interest in textile preforms has been as a result of the available automated textile processing coupled with controlled fiber distribution (and hence improved properties). Using standard textile machinery, it has been possible to create flat and near-net-shape complex preforms for engineering applications through weaving, knitting, braiding, and stitching technologies [9].

Composite preforms are also manufactured by filament winding tows onto a mandrel as proposed by Howell and Roundy [10]. The benefits expected from this technique include low cost, high-fiber volume fraction, controlled filament angle and a continuous filament on mandrel composite preform. A preform with varying fiber orientations can be produced using infinite number of filament winding angles, unlike braid or fabric preforms. Moreover, since the preform is filament wound directly onto a mandrel, fiber distortion and fabrication time are reduced. With fabric or braided preforms, often an additional secondary step is required to transfer the materials onto a mandrel to prepare for a preform for Resin Transfer Molding (RTM).

Braiding is a method of interconnecting strands into fabrics or reinforcements. Yarns in braid direction interlace each other to form preforms in the form of tubes, narrow flat strips, or solid 3D structures [11].

Weaving entails warp yarns in the fabric direction interlacing with weft yarns at 90° to form the fabric. In the case of knitting operations, sheets, or tubes are formed by interlooping yarns with each other. If required, other yarns may be in cooperated to the knitted structure and held in by the loops. Other preform formation methods include entangling (needled fabrics), bonding, and stitching.

The composite processing technologies, including the number of yarns introduced and their direction and fabric formation principle utilized are provided in Table 1.

This article reviews the previous and ongoing research on preforms as well as the techniques used in their manufacture and their utilization in engineering composites.

Table 1. A comparison between different fabric formation techniques (reproduced with kind permission from NISCAIR [12]).

Textile technology	Yarn introduction direction	Fabric formation principle
Weaving	Two (0°/90°) (warp and weft)	Interlacing (by selective insertion of 90° yarns into 0° yarn system)
Knitting	One (0° or 90°) (warp or weft)	Interlooping (by drawing loops of yarns over previous loops)
Braiding	One (machine direction)	Intertwining (position displacement)
Nonwoven	Three or more (orthogonal)	Mutual fiber placement

CLASSIFICATION OF PREFORMS

Composite preforms are commonly classified as either 1D, 2D, 2.5D, or 3D. One dimensional preforms include twisted and untwisted fiber tows and spun yarns. Two dimensional preforms are mostly manufactured by 2D weaving, the most common weaving process. This weaving method involves interlacing two orthogonal sets of threads termed warp and weft to form a fabric. A 2.5D fabrics are pile fabrics produced on a conventional 2D weaving machine using ground warp, pile warp, and pile weft sets of yarn.

The conventional 2D weaving technique can be designed in such a way to permit the warp and weft yarns to be interlaced with binder warp yarns or interlacer yarns in the through-the-thickness direction (*z*-direction). Such a multilayer weaving produces a so-called interlaced 3D fabric [9]. A specifically designed 3D weaving machine can be used to produce a fully interlaced 3D fabric, whereby all the three sets of yarns are interlaced. Through the use of a special binding process, three orthogonal sets of yarns can be connected together without weaving, knitting or braiding by a non-interlaced fabric forming process often known as nonwoven.

The weaving of multilayer textile preforms consists of interlacing three sets of yarns and orienting them into three mutually perpendicular directions via an appropriate weave architecture and lift plan. Many specialized weaving machines have been developed to manufacture multi-directional preforms. However, due to the cost of these machines, conventional Dobby and Jacquard weaving could still be better alternative. A technique to manufacture multilayer woven textile preforms using a Jacquard shedding mechanism has been described in a patent [13]. Ruzand and Guenot [14] presented the first patent on modification of a standard loom (with lappet bar pairs on top and/or bottom of the fabric) to carry out a multi-axial weaving. Farley [15] also developed a multi-axial weaving process based on lappet weaving.

Table 2. Types of fabric and preform construction (reproduced with kind permission from Wiley-VCH [11]).

Type	Variations	Construction
Uniaxial (1D)	Uniaxial	Uniaxial tape
		Laminate
Biaxial (2D)	Biaxial 2D	Warp fibers stitched together
		Uniaxial filament winding
		Fabric with warp and fill interlock
Triaxial (3D)	Biaxial 3D	Biaxial 2D braiding
	Triaxial 3D	Filament winding
		Fabric with layers of warp angle interlock
		Filament winding with layer angle interlock
		Triaxial 3D braiding
Multiaxial/ multidirectional	Cartesian 3D (orthogonal)	Fabric with layers of warp angle interlock with stuffers in warp direction *x*-, *y*-, *z*-axes orthogonal to each other
	Polar 3D	Axes of fiber oriented in polar coordinates
	Tetraxial 3D/4D	*x* and *y* fibers at 45° to each other along *z*-axis
	Pentaxial 3D/5D	± 45° in-plane reinforcement with respect to *x*–*y* along *z*-axis
	Heptaxial 3D/7D	Additional face and diagonal fibers
	Undecaxial 3D/11D	Additional face and diagonal fibers

Knitted preforms have enabled the manufacture of complex shaped products, such as jet engine vanes, T-shaped connectors, helmets, medical prostheses, car wheel wells, and aerospace fairings [16]. Deep drawn weft-knit preforms have found use in bone plate implants where the extensibility of preform is utilized to adapt to the underlying bone [17,18].

Other preforms include multi-axial multi-ply fabrics (MMFs). The construction of these preforms show individual unidirectional plies arranged in different directions and stitched together by suitable stitching yarns [19]. Various preform constructions utilized in the composites industry are illustrated in Table 2.

MANUFACTURE AND CHARACTERISTICS OF PREFORMS

One Dimensional Preforms

Unidirectional fibrous preforms, such as fiber tows (rovings) and yarns are the simplest types of preforms. They can be used directly in composites

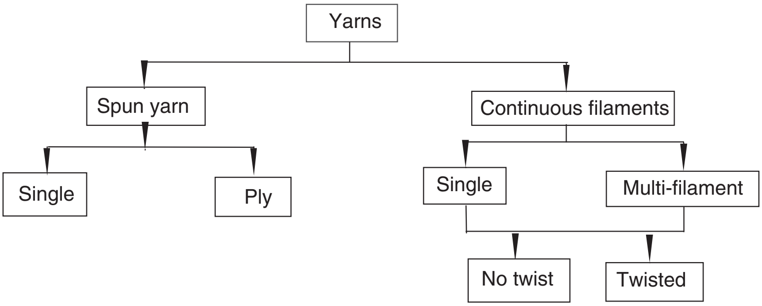


FIGURE 1. Classification of textile yarns (reproduced with kind permission from Katholieke Universiteit Leuven [20]).

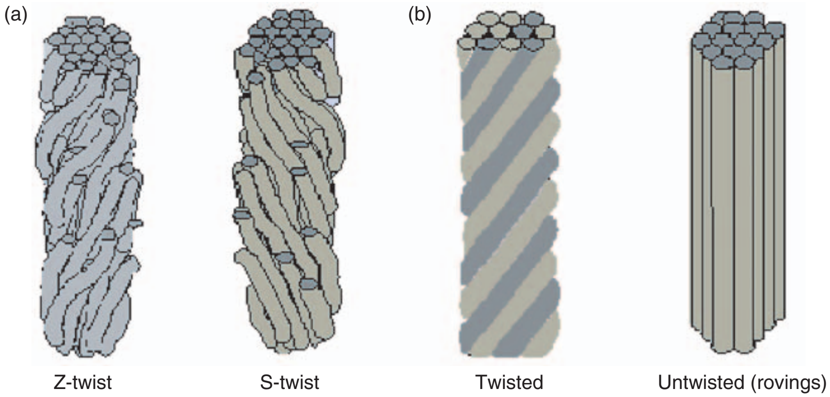
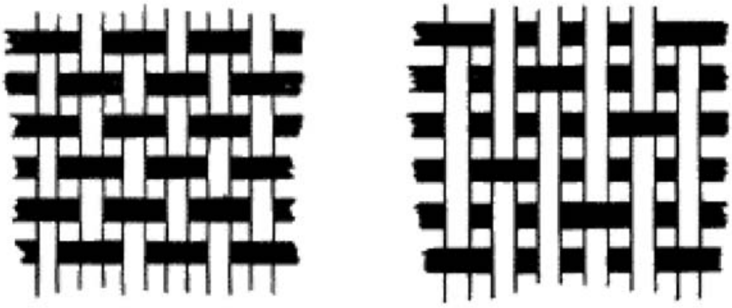


FIGURE 2. Types of unidirectional 1D preforms (reproduced with kind permission from Katholieke Universiteit Leuven [20]). (a) Spun yarn, **(b)** continuous-filament yarns.

manufacture as is the case in filament winding and pultrusion, but they are often used as intermediate for 2D and 3D preforms. Textile yarns are classified as ‘spun’ or ‘continuous’ as illustrated in Figure 1.

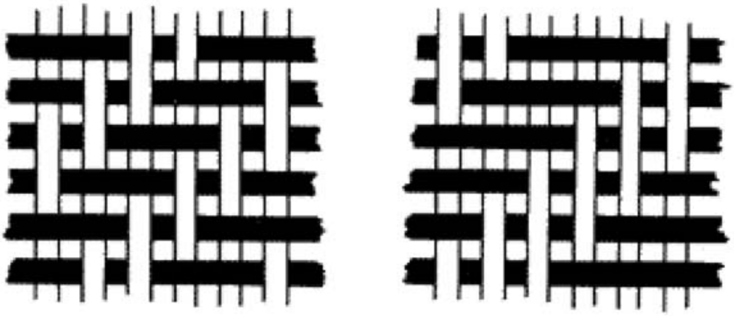
A yarn, which may be defined as linear assemblage of fibers formed into a continuous strand having textile characteristics, can be either spun (Figure 2(a)) or filament yarn (Figure 2(b)). The yarns may be impregnated with polymer by liquid (by passing it through liquid resin bath) or solid (by filling the yarn with a fine powder or use commingling thermoplastic yarn with reinforcing yarn) processes. These preforms can be impregnated and processed using RTM [21] and autoclave, among other methods.

One-directional (1D, unidirectional) preforms have an architecture that is highly unbalanced and is suitable for applications that require axial



Plain weave

5-Harness satin weave



2/2 Twill weave

3/3 Twill weave

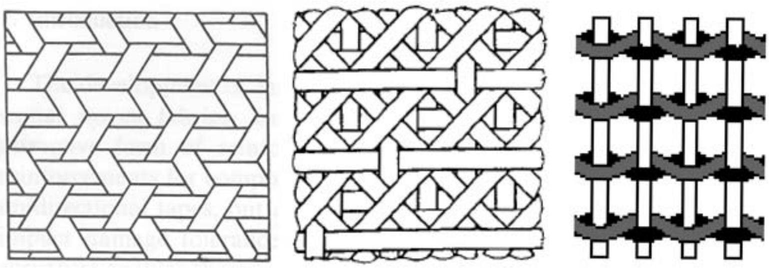
FIGURE 3. Biaxial woven constructions (reproduced with kind permission from Fiber Materials, Inc. [23]).

symmetry along the fiber axis. Wrap yarns are typically stitched to hold them together [11].

Two and Higher Dimensional Preforms

Woven Preforms

Figures 3 and 4 schematically demonstrate conventional 2D fabrics. Plain-woven fabrics are symmetrical and although they have good stability, they are the most difficult to drape. These fabrics are characterized by high crimp and hence show low composite mechanical properties. However, the plain-weave resists shear deformation possibly because it is the most highly interlaced and tightest of basic fabric weaves, albeit these characteristics make this most common weave difficult to impregnate with commonly used resins in composites manufacture. On the other hand, satin weave exhibits minimum interlacing and as such exhibits reduced resistance to shear



Triaxial weaves Quadri-axial weaves Uni-axial weaves (leno)

FIGURE 4. Uni-axial and multi-axial woven constructions (reproduced with kind permission from Katholieke Universiteit Leuven [20]).

distortion. However, with increased number of harnesses, its ability to conform to complex contour shapes (drapeability) increases. Other advantages that make satin weaves important for applications such as in aerospace include their high tensile and flexural strengths and minimum thickness.

Basket weave is a variation of plain weave in which two warp and two weft yarns are interlaced. It offers improved drapeability over the plain weave though not as high as the twill weave. A twill woven fabric forms a characteristic diagonal line on the fabric surface. It has a smoother surface and is easier to wet out than plain woven fabrics. Its reduced crimp contributes to slightly better mechanical properties than the plain woven. A satin construction has minimum interlacing and crimp resulting in highly flexible fabric and good mechanical properties of the composites [22].

Special weaving looms can be used to produce other weaves, such as uni-axial as well as multi-axial. Leno fabrics are used to improve stability in open fabrics. Due to their open structure, leno fabrics can only be used in conjunction with other fabrics to produce composites components [16]

THREE DIMENSIONAL PREFORMS

Three dimensional preforms are either sandwich or solid types.

THREE DIMENSIONAL SANDWICH PREFORMS

The sandwich preform construction is depicted in Figure 5.

The sandwich weaving consists of two layers of 2D-weaves connected by pile yarns. They are woven on a loom similar to that used for velvet or carpet weaving; the difference being cutting at the end is omitted. If required, cutting at the end may be done to produce fabrics popularly referred to as 2.5D (Figure 6).

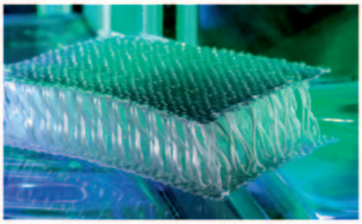


FIGURE 5. Construction of 3D sandwich fabrics (reproduced with kind permission from Katholieke Universiteit Leuven [20]).

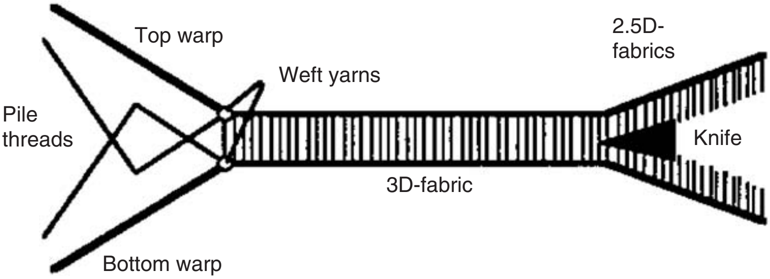


FIGURE 6. Construction of 3D sandwich fabrics and 2.5D fabrics (reproduced with kind permission from Elsevier [24]).

The skin and core connection is a source of weakness in a sandwich structure during loading [25–27]. Manufacturing sandwich structures by velvet weaving, a variant of weaving discussed by Vuure et al. [24] and schematically shown in Figure 6 gives a high skin-core debonding resistance.

SOLID 3D PREFORMS

Solid 3D fabrics constitute multiple layers of weft and warp yarns interconnected possibly with Z-yarns. There are four basic textile-manufacturing techniques that are capable of fabricating solid 3D textile reinforcements: weaving, knitting, braiding, and stitching [28,29].

3tex commercialized a manufacturing process for 3D orthogonal woven fabrics [30]. These materials have been extensively used as preforms for the manufacture of composites for defence, aerospace, automotive, and other sectors.

Three dimensional fabrics do not require additional binding yarns. The 3D weaving technique provides structural features and performance characteristics, such as a through the thickness reinforcement that substantially reduces the possibility of delamination. These preforms have filled a ‘gap’ that existed in the world of composites. While unidirectional composites are transversely isotropic (i.e., having identical properties in both transverse directions, but not the longitudinal direction), laminated composites are generally monoclinic. In other words they have good in-plane properties, but very poor out-of-plane properties. Though 3D woven and 3D braided composites are generally anisotropic, they can be made quasi-isotropic through various weaving and braiding techniques and this with the obvious advantage of being much lighter than the isotropic metals.

Three dimensional fabrics have better permeability than stacked 2D ones and easily wet-out through the z-yarns that act as capillary channels. The faster and easier wet-out results in reduced cycle time, saving on production costs per unit [31]. The obvious advantage of the *z*-direction reinforcement is the improved out-of-plane properties, including impact tolerance. Composites made from 3D preforms exhibit better tensile, flexural, and compressive stiffness and strength than their 2D counterparts. Furthermore, 3D weaving enables near-net fabrics to be molded into components like I-beams, stiffened panels or even 3D ceramic composites for parts that require thermal shock resistance, such as rocket motor nozzles [32]. The 3D preforms find applications in the aerospace, maritime, infrastructure, and medical fields.

In spite of these positive attributes, some researchers have reported a 10–50% decrease in the in-plane properties of 3D preforms as a result of weaving, compared to 2D preforms [33–36]. The lower properties could be due to increased crimping and fiber misorientation during insertion of *z*-binder yarns, as well as fiber damage.

The inclusion of *z*-axis yarns in 3D weaving results in a very robust structure with high interlaminar strength and damage tolerance. The highly automated computer controlled looms ensure high production of quality products. Automatic weaving consists of shedding, picking, and beating-up mechanisms. These mechanisms work in tandem to enable the warps and wefts to be interlaced to form woven fabrics. Two other mechanisms namely let-off and take-up are engaged for continuous weaving operations.

Weaving techniques such as lappet weaving, tri-axial weaving, and pile weaving [37–40] have been extensively reported in the literature.

BIAXIAL 3D PREFORMS

The biaxial 3D weaving may be designed in such a way that the warp yarn passes completely through the thickness or interlocks only the adjacent layers. The alternative is to have the warp yarn directed in such a way that it interlocks any number of adjacent layers.

MULTIDIRECTIONAL PREFORM CONSTRUCTION

The advantage of composites design over design with conventional materials is that the fibrous reinforcement can be placed in the direction where strength is required. Such efficient utilization of the load bearing reinforcement is employed in the design and construction of multi-directional preforms. In case where isotropic composite materials are required, a balanced weave would be most desirable. However, it might be necessary to insert diagonal fibers if shear strength is important in the reinforcement [11].

THREE DIMENSIONAL ORTHOGONAL PREFORM

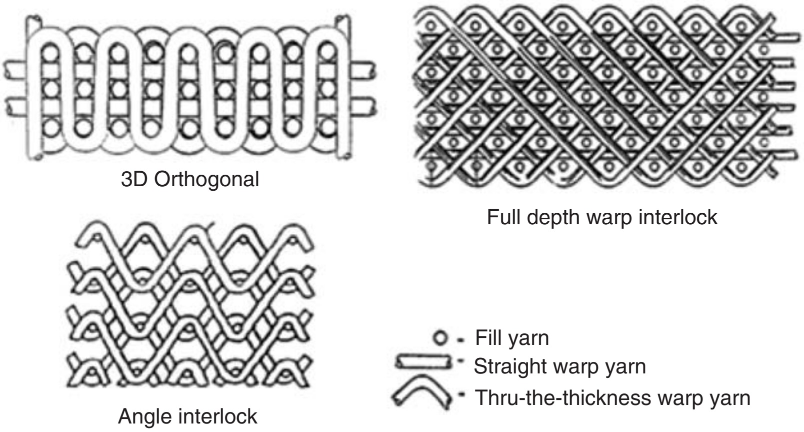
This common multi-directional preform is also referred to as block preform. It helps to achieve optimum material design through flexible orientation and spacing of selected yarns.

Orthogonal and/or angle interlocked multi-layer woven fabrics are woven using multi-warp weaving methods [28].

Angle interlock is similar to biaxial 3D weaving with layer angle interlock while full depth warp interlock is equivalent to triaxial 3D weaving with stuffers in warp direction (Figure 7).

THREE DIMENSIONAL POLAR COORDINATE WEAVE

Figure 8 illustrates a 3D polar coordinate preform. The polar coordinate 3D weave finds use in cylindrical shapes. As in the case of 3D orthogonal preforms,


3D Orthogonal

Full depth warp interlock

Angle interlock

FIGURE 7. Multidirectional preforms (reproduced with kind permission from Fiber Materials, Inc. [23]).

optimum composite design is achieved through optimizing the type and amount of fibers and their spacing in the axial, circumferential, and radial directions. Typical such parameters are indicated in Table 3.

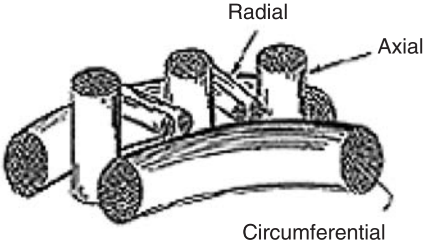
A typical 3D polar weaving loom was developed by Yasui et al. [42]. According to the authors, the loom is capable of making up to 24 layered preforms with through-the-thickness reinforcement using rapier needles.

TETRAXIAL 3D OR 4D PREFORM CONSTRUCTION

A 4D construction as indicated in Figure 9 is basically a 3D orthogonal structure that has been interlaced with *x*-and *y*-direction fibres at 45° axis.

PENTAXIAL 3D OR 5D

There is a similarity between a 5D design and 4D, the difference being the ±45° weave configuration in-plane reinforcement with respect to the *x*–*y* fibers along the *z*-axis.



3D Cylindrical

FIGURE 8. Three Dimensional Polar Coordinate Preform (reproduced with kind permission from Fiber Materials, Inc. [23]).

Table 3. Typical characteristics[a] of 3D polar coordinate preforms (reproduced with kind permission from The Minerals, Metals & Materials Society [41]).

	Weave spacings (mm)			Fiber volume (%)			
Diameter (mm)	z	θ	r	z	θ	r	Total
99	1.5	1.8	2.8	15	23.2	9.3	47.5
286	1.6	2.3	2.7	11.8	22.1	13.2	47.1
500	1.4	8.7	1.4	6.0	30.0	3.9	39.9
1156	1	2	1.7	11	23	11	45

[a] z = axial direction, θ = circumferential direction, r = radial direction.

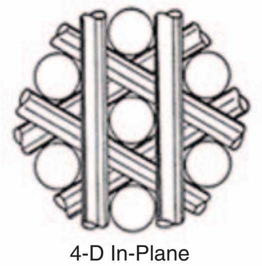


FIGURE 9. Four-dimensional woven construction (reproduced with kind permission from Fiber Materials, Inc. [23]).

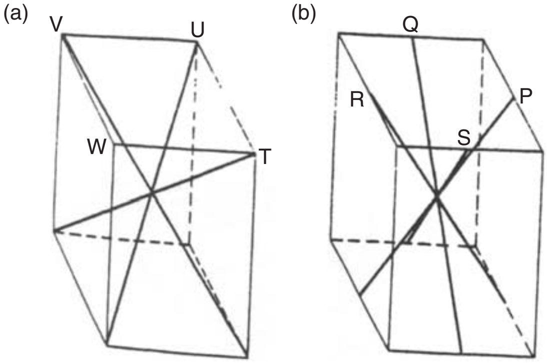


FIGURE 10. (a) Typical 'across the corners' diagonals 7D construction – type 1 and (b) typical 'across the face' diagonals 7D construction-type II (reproduced with kind permission from Wiley-VCH [11]).

HEPTAXIAL 3D OR 7D

As shown in Figure 10(a), one type of 7D design can be produced by diagonally reinforcing across corners T, U, V, and W, in combination with the basic 3D *x*, *y*, and *z* yarns. Another type of 7D is constructed by placing diagonal yarns across the face of the preform as indicated in Figure 10(b). In both cases, elimination of the baseline 3D orthogonal portion would produce a 4D construction.

UNDECAXIAL 3D OR 11D

An 11D design is produced by combining the two methods of making 7D design (i.e., diagonal across the corners and diagonal across face to face) with the 3D base structure (Figure 11). The 11D is an isotropic structure.

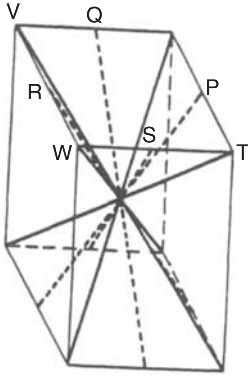


FIGURE 11. Typical 'across the corners' diagonals plus 'across the face' diagonals 11D construction (reproduced with kind permission from Wiley-VCH [11]).

Braiding

2D BRAIDS

Braiding occurs through the alternate exchange of rows and columns of yarn carriers.

Braided preforms manufacturing technology has attracted a lot of interest because of the through-the-thickness strength and increased damage tolerance the preforms provide to structural applications. Moreover, cost savings are significant, thanks to the automation of the manufacturing process. However, braids exhibit reduced in-plane properties due to the yarn path relative to the axial direction.

Smith and Swanson [43] have investigated the biaxial strength properties of 2D triaxial braid materials using four sets of architectures. The researchers report reduced strengths in the axial direction compared to the corresponding laminates of similar fiber and matrix materials.

Two-dimensional braids can be either soutache, tubular, or flat [28]. Most of braiding for composites is horizontal, though braiding can also take place vertically. The braiding process has been successfully used with glass, aramid, carbon, ceramic, and metallic fibers. Structural applications of braided composites range from rocket launchers to automotive parts to aircraft structures [44].

Braiding can be classified into conventional braids and formed braids. In the case of conventional braids, the fabrics are formed in space and rolled around a take-up mechanism, while formed braids are directly braided on to a mandrel. Filament winding presents a good example where a shaped mandrel is covered with a braided fabric resulting in a near-net-shape manufacturing [45].

Braids are constructed in either flat or tubular configurations. While the former are used primarily to selectively reinforce certain areas, such as in pultruded parts, tubular braids produce hollow cross-section in parts, such as windsurfer masts, as well as lamp and utility poles pultruded over a suitable mandrel [37].

A biaxial braid is in fact a variation of 2D weaving. Its importance lies in its ability to conform to various shapes. Preforms that require high tensile strength are braided at small angles (~10°), while those for torsional strength are braided at 45°. For improved hoop strength, braiding angles of ~85° are utilized [11].

THREE-DIMENSIONAL BRAIDS

Braiding has gained popularity in manufacturing preforms because it can produce more complex 3D structures than any of the other textile processes. The properties of composites based on 3D preforms are influenced by the fiber volume fraction as well as the proportion of fibers in each of the x, y, and z directions. Manufacture of these 3D braided preforms can be by conventional horn-gear machine or by modifying a conventional braiding machine. Other braiding machines include a track and column [46], a 2-step [47], a 4-step [48], and a matrix loom [49]. The complexity of braided shapes is due to the fact that braids exhibit a large convergence zone in which yarns are literally tensioned into the final pattern, such tensioning enables fabric to be formed over a complex shaped mandrel [11]. Since the fibers conform well to the mandrel, it is possible to braid different geometries, such as cylindrical, square, hexagonal, etc. An illustration of a typical braid construction is depicted in Figure 12.

Three-dimensional braiding is capable of inter-twining tows to produce thick and net section preforms in such a way that distinct layers are almost entirely eliminated [50]. Normal braided preforms can be of constant cross-section, while more complex ones can be created by braiding onto a suitable mandrel. Pre-impregnated fibers can be braided and the part transferred for curing [51].

The 3D braided preforms boast of increased structural integrity as well as a higher possibility of near net shape manufacturing. The impact properties and damage tolerance are notably higher with respect to traditional laminated composites [52]. 3D composites have a greater transverse strength than 2D composites possibly because they lack interlaminar zones that are known to favor propagation of delamination cracks. Further, 3D braided tubular preforms have been speculated to exhibit greater energy absorption capability than the corresponding 2D braided tubular ones [53].

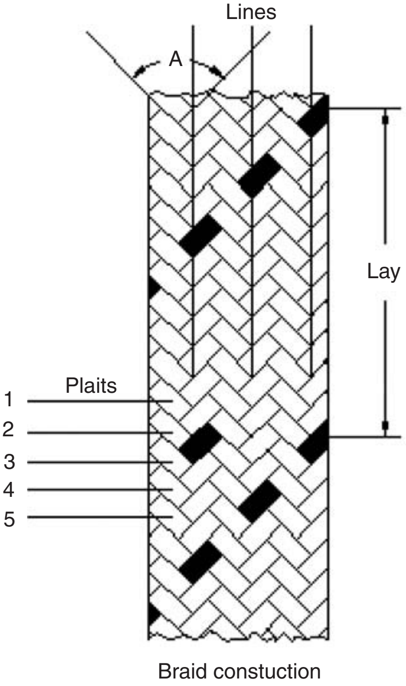


FIGURE 12. Schematic of braid construction (reproduced with kind permission from Fiber Materials, Inc. [23]).

During braid formation, there is no beat-up of filling or weft as is the case with woven structures, hence the relatively low shear resistance exhibited by braided structures and the corresponding high deformability in the axial and radial directions. These characteristics of braided structures permit production of near-net-shape structures in addition to enabling the former to conform to varying cross-sectional shapes such as cones and nozzles. Due to the high torsional stiffness of braids, tubular braided composites are used in the manufacture of vehicle drive shafts [22].

With net-shape manufacturing, complex preform structures very similar to the required finished products can be produced without the need for scrapping and post-processes machining operations.

Braiding has been successfully utilized in many critical applications in shaped parts because of its structural integrity, durability, design flexibility and precision [45]. A major limitation in 3D braiding is that the machine size determines the maximum preform size and therefore most braiding machines are able to produce braided preforms of small dimensions only. The machines are also slow and have short production runs. Despite their structural advantages, 3D braids are not able to adequately compete in cost with 2D braids and laminates [37,54,55].

TRIAXIAL 3D BRAIDS

Triaxial braiding is similar to 3D weaving [11]. The braids are constructed by inserting a third yarn parallel to braid axis to increase tensile strength and stiffness. The braiding and preform curing processes are carried out on a mandrel.

Mats and Nonwovens

Nonwovens are fibrous assemblies converted into fabric by chemical, thermal, or mechanical means and often a combination of these methods. The densities are somewhat lower than those suitable for structural applications as they range from $10\,\mathrm{g/cm^2}$ to $100\,\mathrm{g/cm^2}$. However, use of nonwoven preforms in automotive and marine applications is continually increasing. New developments, such as impregnation of nonwoven mat of continuous acrylic filaments with ceramic or metal matrix have extended applications of nonwoven composites to construction, aerospace, filtration, industrial, medical protection, sporting, and transportation fields [56].

Mats are classified as either chopped strand mat or continuous strand mat (continuous filament mat). These two types of reinforcements do not show a dramatic difference in the resulting mechanical properties of the composites. To produce continuous strand mats, continuous yarns are swirled onto a moving carrier film or belt and subsequently held together by a thermoplastic polymer binder. On the other hand, chopped strand mats are produced by chopping continuous fibers into lengths of ~25 mm and depositing them onto a carrier film or a perforated mould. A binder is used to hold the fibers together.

The chopped mats can be compression molded to manufacture the preforms. The heated thermoplastic binder helps to mold the fibers into net-shape, which is further cooled to set the shape [22]. The preforms are then used in Resin Transfer Molding (RTM) or Vacuum Assisted Resin Infusion [VARI].

Nonwovens find use in many technical applications in composite preforms that often require 3D nonwoven constructions. These preforms are prepared from flat webs, in a process associated with high cost due to the necessary conversion process, and uneven final product as a result of joints. Gong et al. [57] report a 3D nonwoven preform production technique directly from staple fibers. The process, claimed to be efficient by the authors, uses air-laying principle to form the web and thermal through-air bonding method for the web consolidation. The fibers are placed on a porous mold in the form of a web, the latter being consolidated to form the final product. Regulation of the airflow as per the shape of the mold ensures that an even product is produced. An even fiber distribution around the whole 3D mold can be achieved by varying the local porosity as suggested by Ravirala and Gong [58].

Directed Fiber Preforming (DFP) is an important technique used in the manufacture of nonwoven preforms. The manufacture of complex 3D preforms by directed fiber preforming has significant process features, such as excellent repeatability and minimal wastages. Moreover, since tows or rovings are used as reinforcement instead of woven fabrics, there are cost benefits of DFP in composites manufacture. In this method a robot-mounted mechanical chopper head is used to spray chopped fibers and a polymeric powdered binder onto a perforated tool face.

The preform thickness is controlled by compressing the fibers with a matched perforated tool as hot air is cycled through the perforations for the purpose of consolidating the binder. The preform is then transferred to a separate mold and injected with resin to make the composites [60]. Preforms for a boat deck and lampshade are good examples of the directed fiber preforming process.

Knitting

Knitting is an alternative to weaving in which a looser and more flexible fabric is produced by either weft knitting (one yarn used) or warp knitting (multiple yarns used).

Previously, knitted preforms were underutilized because of their perceived extensible and unstable structure. However, knitted preforms have rekindled attention with a growing awareness of their formability and 3D net-shaping. But as would be expected, the highly curved fiber architecture of knits causes lower in-plane strength and stiffness compared to unidirectional and woven fabric composites. But knitted composites show excellent out-of-plane properties and energy absorption capability [8].

The high extensibility, previously considered a drawback to the use of knits as composite reinforcements, comes in handy in the manufacture of complicated composite parts [61]. Further to the use of knitted structures in thermoplastic and thermoset reinforced rigid composites, these preforms are also used to reinforce elastomers. The energy absorption capacity of the loop structures has been shown to positively contribute to the good impact and delamination resistance of knitted preform composites. Though the impact performance of knitted composites is improved by the yarn architecture of the knit, the structural performance is low [62].

The increased use of 3D multiaxial warp knitted (MWK) fabric preforms has been associated with their reported low production cost, high production efficiency, structural integrity, flexibility in design, high tear resistance, and improved through-the-thickness strength [63]. The structure of MWK is represented by two diagonal weft yarns, a warp yarn, and a horizontal weft yarn. The structure is produced on a special raschel machine and pillar stitches are utilized to hold the layers from both sides [39].

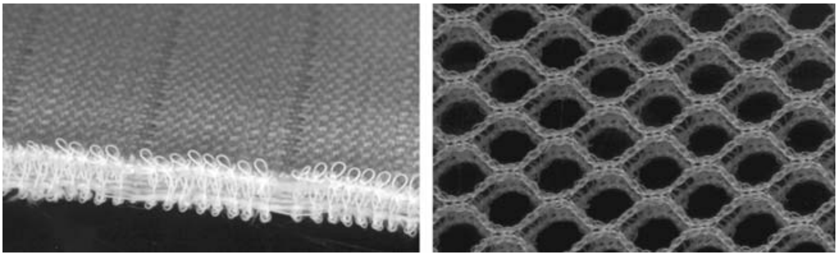
Sandwich 3D knitted preforms are knitted on Raschel knitting machines, such as the double-bed. Closed and open skin 3D knitted sandwich preforms are illustrated in Figure 13. The open 3D-knits have demonstrated excellent drapability as well as ventilating properties.

Stitching

Stitching methods were developed as a result of inherent poor impact, in-plane shear properties, and poor delamination resistance of composites manufactured from woven structures. But just like weaving, stitching also reduces mechanical properties of the reinforcing fibers [37].

Stitching is either used to assemble and hold together single or multilayered textile preforms or to increase impact resistance by addition of through-the-thickness reinforcement [64]. It offers distinct advantages particularly if the preforms are to be utilized for complex shaped structures [65]. However, stitching of preforms creates faults in the plane of the material and this damage has an adverse effect on the mechanical properties of the composites [66–69].

Cut-and-sew preforming can be used to convert 2D to 3D shapes ready for molding [51]. The preform materials are kept in place by sewing or stitching. The advantage of this preforming method is the expected reduction in production cycle times since the cut-and-sew usually takes place outside the mold.



Closed skin 3D-Knitted sandwich

Open skin 3D-Knitted sandwich

FIGURE 13. Closed and open skin 3D knitted sandwich preforms (reproduced with kind permission from Katholieke Universiteit Leuven [20]).

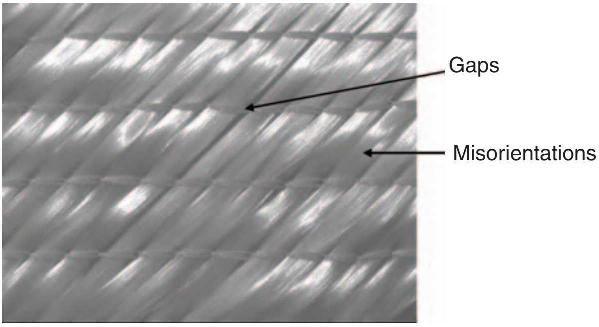


FIGURE 14. Gaps and misorientation in stitched preforms (reproduced with kind permission from Katholieke Universiteit Leuven [20]).

Noncrimp fabrics, also known as inlaid, have become increasingly popular in the recent past. The development of these fabrics was after realization that the highly crimped yarn resulting from the traditional 2D weaving, though a fast and economical process, led to reduced composite properties. The manufacture of noncrimp fabrics (NCFs) involves laying tows flat, straight and fully extended, and subsequently knitting/stitching by fine filaments, such as polyester thread to keep the tows in place [28]. Several angle layers can also be laid in different direction to produce multi-layer noncrimp fabric constructions.

Due to the absence of crimp, NCFs exhibit better mechanical properties than the corresponding weaves. Moreover, since multiple layers can be used in one preform, there is considerable labor time saving because of precise rapid layup of multilayered reinforcement. However, some stitch-induced problems, such as gaps and in-plane fiber misorientations (Figure 14) can be expected.

The development of textile reinforced composites with optimum performance requires use of preforms comprising high flexibility, formability, stability, high axial rigidity, and desired permeability.

CONCLUSIONS

The advancement of preforming technology, encouraged by the development of automated production and active research has contributed to the renewed interest in the design and manufacture of preforms for engineering composites. From the trend established in this review, the production can only become more sophisticated and thus a spin-off into more and new applications of preforms in the field of composites will be witnessed. The successes witnessed in solving, to a great extent, the low out-of-plane impact properties of preforms designed for in-pane applications, by incorporating through-the-thickness reinforcement in 3D preforms, are likely to be taken further. Future research is, therefore, likely to produce even more innovative multi-directional preforms suitable for diverse applications in the composites industry.

REFERENCES

1. Luo, R., Yang, C. and Cheng, J. (2002). Effect of Preform Architecture on the Mechanical Properties of 2D C/C Composites Prepared Using Rapid Directional Diffused CVI Processes, *Carbon*, **40**: 2221–2228.
2. Hamada, H., Sakaguchi, M., Nakai, A. and Takeda, N. (2000). The Mechanical Properties of Unidirectional Thermoplastic Composites Manufactured by Micro-Braiding Technique, *Composites Science and Technology*, **60**: 717–722.
3. Reinforced Plastics (2002) September: 56–58.
4. Wang, J., Paton, R. and Page, J.R. (1999). The Draping of Woven Fabric Preforms and Prepregs for Production of Polymer Composite Components, *Composites: Part A*, **30**: 757–765.
5. Grujicic, M., Chittajallu, K.M. and Walsh, S. (2004). Effect of Shear, Compaction and Nesting on Permeability of the Orthogonal Plain-weave-fabric Preforms, *Materials Chemistry and Physics*, **86**: 358–369.
6. Talvensaari, H., Ladstätter, E. and Billinger, W. (2005). Permeability of Stitched Preform Packages, *Composite structures*, **71**: 371–377.
7. Sharma, S.B., Potluri, P., Atkinson, J. and Porat I. (2001). Mapping of Tubular Woven Composite Preforms on to Doubly-curved Surfaces, *Computer-Aided-Design*, **33**: 1035–1048.
8. Kim, K.-Y., Curiskis, J.I., Ye, L. and Fu, S.-Y. (2005). Mode-I Interlaminar Fracture Behaviour of Weft-knitted Fabric Reinforced Composites, *Composites: Part A*, **36**: 954–964.
9. Soden, J.A. and Hill, B.J. (1998). Conventional Weaving of Shaped Preforms for Engineering Composites, *Composites Part A*, **29**: 757–762.
10. Howell, D.D. and Roundy, F.E. (1999). Filament Wound Preforms for RTM, 31st SAMPE International Technical Conference, Chicago, IL, October 26–30.
11. Lee, S.M. (ed.) (1993). *Handbook of Composite Reinforcements*, Wiley-VCH, California.
12. Ogale, V. and Alagirusamy, R. (2004). Textile Preforms for Advanced Composites-Review Article, *Indian Journal of Fibre and Textile Research*, **29**: 366–375.
13. Mood, G.I. and Mahoubian-Jones, M.G.B. (1992). International Patent WO 9214876, 3 (Bonas Machine Co. Ltd), 3 September.
14. Ruzand, J.M. and Guenot, G. (1994). Multiaxial Three-dimensional Fabric and Process for its Manufacture. International Patent WO 94/20658, 15 September.
15. Farley, G.L. (1993). Method and Apparatus for Weaving a Woven Angle Ply Fabric, US Patent 5 224 519, 6 July.
16. Alagirusamy, R., Fangueiro, R., Ogale, V. and Padaki, N. (2006). Hybrid Yarns and Textile Preforming for Thermoplastic Composites, *Textile Progress*, **38**(4): 18–37.

17. Savci, S., Curiskis, J.I., Pailthorpe, M.T. (2000). A Study of the Deformation of Weft-knit Preforms for Advanced Composite Structures Part 1: Dry Preform Properties, *Composite Science and Technology*, **60**: 1931–1942.
18. Mayer, J., Ha, S.W., Ruffiex, K., Tognin, R., Kock, B. and Wintermantel, E. (1994). Knitted Fibre Reinforced Composites, *Automotive Engineering*, **August**: 21–24.
19. Truong, T.C., Vettori, M., Lomov, S. and Verpoest, I. (2005). Carbon Composites Based on Multi-axial Multi-Ply Stitched Preforms: Part 4 Mechanical Properties of Composites and Damage Observation, *Composites: Part A*, **36**: 1207–1221.
20. Verpoest, I. and Lomov, S. (2007). Unpublished data, Katholieke Universiteit, Leuven, Belgium.
21. Jia, Y. et al. (2006). Mesoscopic Simulation of the Impregnating Process of Unidirectional Fibrous Preform in Resin Transfer Moulding, *Materials Science and Engineering*, **435–436**: 515–520.
22. Astrom, B.T. (1997). Manufacturing of Polymer Composites, Chapman and Hall, London, UK.
23. http://www.fibermaterialsinc.com/frSW.htm as on 3rd October, 2007.
24. Van Vuure, A.W., Ivens, J.A. and Verpoest, I. (2000). Mechanical Properties of Composite Panels Based on Woven Sandwich-fabric Preforms, *Composites Part A*, **31**: 671–680.
25. Zenkert, D., and Falk, L. (1991). Interface Debondings in Foam Core Sandwich Beams and Panels, In: *Proceedings of ICCM-8, Honolulu*, July, 3H1-3H10.
26. Zenkert, D. (1997). *The Handbook of Sandwich Construction*, p. 393, EMAS, West Midlands, UK.
27. Offringa, A.R. (1994). Structural Thermoplastic Aircraft Floor Panels-in Series Production, In: *Proceedings of 39th International SAMPE Symposium*, April, 1905–1916.
28. Chiu, C.-H. and Cheng, C.-C. (2003). Weaving Method of 3D Woven Preforms for Advanced Composite Materials, *Textile Research Journal*, **73**(1): 37–41.
29. Ko, F. (1988). Three-dimensional Fabrics for Composites, In: *Textile Structural Composites*, Chou, T.W. and Ko, F.K. (eds.), pp.129–171, Elsevier, Amstredam.
30. 3Tex Technologies and Capabilities Guide, http://www.3TEX.com as on 2nd October, 2007.
31. Stobble, D. and Mohamed, M. (2003). 3D Woven Composites: Cost and Performance Viability in Commercial Applications. In: *Proceedings of the 48th International SAMPE Symposium*, Long Beach, California, May 11–15.
32. Rudov-Clark, S., Mouritz, A.P., Lee, L. and Bannister, M.K. (2003). Fibre Damage in the Manufacture of Advanced Three-dimensional Woven Composites, Composites: Part A, **34**: 963–70.
33. Guess, T.R. and Reedy, E.D. (1985). Comparison of Interlocked Fabric and Laminated Fabric Kevlar 49/Epoxy Composites, *Journal of Composite Technology Research*, **7**: 136–42.
34. Brandt, J., Dreschsler, K. and Arendts, F.-J. (1996). Mechanical Performance of Composites Based on Three-dimensional Woven-fibre Preforms, *Composites Science and Technology*, **56**: 381–6.

35. Chou, S., Chen, H.-C. and Wu, C.-C. (1992). BMI Resin Composites Reinforced with 3D Carbon-fibre Fabrics, *Composites Science and Technology*, **43**: 117–28.
36. Lee, L., Rudov-Clark, S., Lee, L., Bannister, M.K. and Herszberg, I. (2002). Effect of Weaving Damage on the Tensile Properties of Three-dimensional Woven Composites, *Composite Structures*, **57**: 405–13.
37. Mouritz, A.P., Bannister, M.K., Falzon, P.J. and Leong, K.H. (1999). Review of Applications for Advanced Three Dimensional Fibre Textile Composites, *Composites: Part A*, **30**: 1445–1461.
38. Kamiya, R., Cheeseman, B.A., Popper, P. and Chou, T.W. (2000). Some Recent Advances in Fabrication and Design of Three-dimensional Textile Preforms: A Review, *Composite Science and Technology*, **60**(1): 33–47.
39. Curiskis, J.I., Durie, A., Nicholaidis, A. and Herszberg, I. (1997). Developments in Multiaxial Weaving for Advanced Composite Materials, In: *Proceedings of ICCM-II, Volume V, Textile Composites and Characterization*, Gold Coast, Australia, July, pp. V86–V96.
40. Ko, F.K. and Kutz, J. (1988). Multiaxial Warp Knit for Advanced Composites, In: *Proceedings of the Fourth Annual Conference on Advanced Composites*, ASM International, pp. 367–370.
41. Lachman, W.L., Crawford, J.A. and McAllister, L.E. (1978). In: Noton, B., Signorelli, R., Street, K. and Phillips, L. (eds.), *Proceedings of the International Conference on Composite Materials*, pp. 1302–1319, Metallurgical Society of the American Institute of Mining, Metallurgical and Petroleum Engineers.
42. Yasui, Y., Anahara, M. and Omori, H. (1992). Three-dimensional Fabric and Method for Making the Same, US Patent 5 091 246, February.
43. Swanson, S.R. and Smith, L.V. (1996). Strength Design with 2-D Triaxial Braid Textile Composites, *Composite Science and Technology*, **56**: 359–365.
44. Ko, F.K. and Du, G.W. (1998). In: Peters, S.T. (ed.), *Handbook of Composites*, pp. 397–424, Chapman and Hall, London.
45. Liao, T. and Adanur, S. (2000). 3D Structural Simulation of Tubular Braided Fabrics for Net-shape Composites, *Textile Research Journal*, **70**(4): 297–303.
46. Florentine, R.A. (1982). Apparatus for Weaving Three-dimensional Article, U.S. Patent 4,312,261.
47. Popper, P. and McConnell, R.F. (1988). Complex Shaped Braided Structures, U.S. Patent 4,719,837.
48. Kostar, T.D. and Chou, T.W. (1994). Microstructural Design of Advanced Multi-step Three-dimensional Braided Preforms, *Journal of Composite Materials*, **28**(13): 1180–1201.
49. Dow, R.M. (1989). New Concept for Multiple Directional Fabric Formation, In: *Proceedings, 21st International SAMPE Technical Conference*, September pp. 25–28.
50. Zhenkai, W. and Jialu, L. (2006). Braided Angle Measurement Technique for Three- dimensional Braided Composite Material Preform Using Mathematical Morphology and Image Texture, *AUTEX Research Journal*, **6**(1): 30–56.
51. Grifin, D.A. (2002). Blade System design studies volume 1: Composite Technologies for Large Wind Turbine Blades, SAND2002-1879, pp. 39–43, Global energy concepts, Washington.

52. Wu, X., Li, J. and Shenoi, R.A. (2006). Measurement of Braided Preform Permeability, *Composite Science and Technology*, **66**: 3064–9.
53. Calme, O., Bigaud, D. and Hamelin, P. (2005). 3D Braided Composite Rings Under Lateral Compression, *Composite Science and Technology*, **65**: 95–106.
54. Li, W. and El Sheikh, A. (1998). The Effect of Process and Processing Parameters on 3D Braided Preforms for Composites, *SAMPE Quarterly*, **19**: 22–28.
55. Popper, P. and McConnel, R. (1987). A New 3D Braid for Integrated Parts Manufacturing and Improved Delamination Resistance-the 2 Step Process, In: *Proceedings of the 32nd International SAMPE Symposium and Exhibition*, pp. 92–93.
56. Tedesco, R., Busato, G. and Sinatora, G. (1991). US Patent, 5 063 099 (To Montefiber S.P.A., Milan, IT), November.
57. Gong, R.H., Dong, Z. and Porat, I. (2003). Novel Technology for 3D Nonwovens, *Textile Research Journal*, **72**(2): 120–123.
58. Ravirala, N. and Gong, R.H. (2003). Effects of Mould Porosity on Fibre Distribution in a 3D Nonwoven Process, *Textile Research Journal*, **73**(7): 588–592.
59. http://www.compositefactory.com/preforms.html as at 3rd October, 2007.
60. Harper, L.T., Turner, T.A., Warrior, N.A. and Rudd, C.D. (2007) Characterisation of Random Carbon Fibre Composites from a Directed Fibre Preforming Process, *The Effect of Tow Filamentisation, Composites: Part A*, **38**: 755–770.
61. Hong, H., DeAraujo, M.D., Fangueiro, R. and Ciobanu, O. (2002). Theoretical Analysis of Load-extension Properties of Plain Weft Knits Made from High Performance Yarns for Composite Reinforcement, *Textile research Journal*, **72**(11): 991–995.
62. Leong, K.H., Ramakrishna, S., Huang, Z.M. and Bibo, G.A. (2000). The Potential of Knitting for Engineering Composites-a Review, *Composites: Part A*, **31**(13): 197–220.
63. Hu, J., Jiang, Y. and Ko, F. (1998). Modelling Uniaxial Tensile Properties of Multiaxial Warp Knitted Fabrics, *Textile Research Journal*, **68**(11): 828–834.
64. Weimer, C. (2003). Preform-engineering:Applied Sewing Technologies to Incorporate Part and Process Functions into Dry Textile Reinforcements, *Composites Science and Technology*, **63**(14): 2089–2098.
65. Bhat, G.S. and Sharma, V. (1994). Three-dimensional Textiles for Composites, In: *Processing and Fabrication of Advanced Materials*, pp. 313–333, The Minerals, Metals and Materials Society, USA.
66. Dransfield, K., Baillie, C. and Mai, Y.-W. (1994). Improving the Delamination Resistance of CFRP by stitching – A Review, *Composites Science and Technology*, **50**(3): 305–317.
67. Holt, H.B. (1992). Future Composite Aircraft Structures may be Sewn Together, *Automotive Engineering*, **90**: 46–49.
68. Mouritz, A.P., Leong, K.H. and Herszberg, I. (1997). A Review of the Effect of Stitching on In-plane Mechanical Properties of Fibre Reinforced Polymer Composites, *Composites Part A*, **28**(12): 979–991.

69. Morlos, A. (1990). Structural Stitching of Textile Preforms, In: *Proceedings of 22nd International SAMPE Technical Conference*, 6–8 November, pp. 1217–1230.
70. Devold AMT (1997). *Promotional material*, Langevag, Norway.

BIOGRAPHY

Prof. Paul Wambua, a Registered Professional Engineer, obtained his PhD in Materials Engineering from the Katholieke Universiteit Leuven, Belgium in 2004. He is an Associate Professor in the Department of Manufacturing, Industrial and Textile Engineering, Moi University, Kenya. A part of the current work was done while he was a postdoctoral fellow at the Council for Scientific and Industrial Research (CSIR), Materials Science and Manufacturing, South Africa. Prof. Wambua has published widely in the area of natural fibre composites and presented many papers in International Conferences. His interests include low and ballistic impact on composites, processing and mechanical testing of Fibre-reinforced composites.