The current issue and full text archive of this journal is available on Emerald Insight at:
www.emeraldinsight.com/1560-6074.htm

Textile technologies for the manufacture of three-dimensional textile preforms

Natalie Ishmael and Anura Fernando
School of Materials, University of Manchester, Manchester, UK
Sonja Andrew
School of Art, Design and Architecture, University of Huddersfield, Huddersfield, UK, and
Lindsey Waterton Taylor
School of Design, University of Leeds, Leeds, UK

Received 28 June 2017
Revised 4 September 2017
Accepted 7 September 2017

Abstract

Purpose – This paper aims to provide an overview of the current manufacturing methods for three-dimensional textile preforms while providing experimental data on the emerging techniques of combining yarn interlocking with yarn interlooping.

Design/methodology/approach – The paper describes the key textile technologies used for composite manufacture: braiding, weaving and knitting. The various textile preforming methods are suited to different applications; their capabilities and end performance characteristics are analysed.

Findings – Such preforms are used in composites in a wide range of industries, from aerospace to medical and automotive to civil engineering. The paper highlights how the use of knitting technology for preform manufacture has gained wider acceptance due to its flexibility in design and shaping capabilities. The tensile properties of glass fibre knit structures containing inlay yarns interlocked between knitted loops are given, highlighting the importance of reinforcement yarns.

Originality/value – The future trends of reinforcement yarns in knitted structures for improved tensile properties are discussed, with initial experimental data.

Keywords 3D textiles, Knitting, Textile composites, Textile preforms, Weaving

Paper type Research paper

1. Introduction

The use of textiles for technical applications has been on the rise, particularly as composites for engineering purposes. Textiles can provide performance advantages, most notably in terms of high strength-weight ratios compared to metal counterparts (Bannister, 2004); this is

---

The authors would like to express utmost thanks to Edward Lay for the manufacture of the experimental samples, and for his expertise in the sample manufacture.

Funding: This work was supported by The Engineering and Physical Sciences Research Council, grant code: P116020.

Research Journal of Textile and Apparel
Vol. 21 No. 4, 2017
pp. 342-362
Emerald Publishing Limited
1560-6074
DOI 10.1108/RJTA-06-2017-0034

ideal for automotive applications, where reduced weight contributes to fuel efficiency and improves ease of handling in the manufacturing process.

Textile composites have been defined as "the combination of a resin system with a textile fibre, yarn or fabric system" (Scardino, 1989). Traditionally, composites are manufactured by manual lay-up of two-dimensional (2D) laminates until the correct thickness and shape is achieved, a costly and labour-intensive method (Mouritz *et al.*, 1999). To overcome these problems, the textile industry has sought to produce near-net-shape reinforced three-dimensional (3D) fibre architectures (Mouritz *et al.*, 1999), known as textile preforms, which are produced directly into the shape of the final component, eliminating the hand lay-up process. As discussed by Ogale and Alagirusamy (2004), textile preforms can be manufactured by weaving, knitting, braiding, stitching or non-woven methods.

3D contoured preforms can be defined as "fully integrated continuous fibre assemblies having multi-axial in-plane and out-of-plane fibre orientation" (Hu, 2008). Mechanical properties can be tailored by orientating fibres in optimal directions to provide through-the-thickness reinforcement, which improves interlaminar shear and prevents delamination; a characteristic that traditional composites lack (Bannister, 2001; Hufenbach *et al.*, 2006). Textile preforms can be injected with resin and subjected to heat and pressure for consolidation into a hard or soft (flexible) textile composite; alternatively, they can remain in their soft state for a range of applications, i.e. padding for sportswear or materials for filtration. The resin contributes only a minor role in the load bearing capacity of the composite (Heenkenda, 1999); instead, it is the reinforcement materials that provide the strength and load bearing capacity. In a soft composite, the textile structure is the major component to the composite (Annis and Quigley, 1998).

The production of 3D fabrics through fully automated textile machinery eliminates assembly operations, minimises waste and reduces cost (Hu, 2008; Ionesi *et al.*, 2010), factors that have led to increased interest in 3D textile preforming. A significant advantage to 3D preforms is their ability to fit exactly into a mould for resin infusion without the need to precisely manoeuvre the textile structure into the correct shape (Heenkenda, 1999).

This paper addresses current technologies that achieve such preforms, and provides an understanding of how a combination of yarn arrangements (interlocking and interlooping) could improve the mechanical and physical properties of a structure. The experimental results of the tensile properties of knit structures with inlay yarns supports further investigations into reinforced contoured material forms.

2. Overview of textile construction processes

Textile forms are categorised as either 2D or 3D based on the degree of reinforcement in the *z* (thickness) direction (Kamiya *et al.*, 2000). Davies (2011) categorises 3D fabrics into two types based on their manufacturing process: those produced in a multi-step process where individual layers of 2D materials are joined together; and those produced in a single-step process creating a dense structure (i.e. multi-axial warp) or a structure with a hollow core (i.e. knitted spacer). Hearle (2015), on the other hand, divides 3D fabrics into two categories based on their form: either a fabric with an overall 3D shape or a fabric containing a complex internal 3D structure. Table I provides examples of 2D and 3D fibre architectures for each of the main textile construction processes.

Each fabric-forming process offers its own benefits and limitations, as summarised in Table II. Woven structures provide the highest strength and stability compared to any other fabric constructed from yarns (Sondhelm, 2000), whereas knitted fabrics can provide high drapeability and extensibility due to easy distortion of the loop structure (Ray, 2012). Developing a method that can produce a contoured form with combined fabric-forming concepts will expand the scope of mechanical properties available in a single structure.

Braiding is typically suited to produce cylinder components where a continuous linear material is produced. However, yarn interlacement can also occur directly over a shaped mandrel or inner core to produce varied shaped composites (Potluri *et al.*, 2003), as shown in Figure 1. Weaving is suitable for high-performance applications, where the nature of straight inlaid yarns provides high strength and stiffness. However, the straightness of yarns can prevent drapeability to complex shapes.

Conversely, the interlooping characteristics of knitted structures provide superior elastic behaviour compared to woven and braided fabrics, contributing to its enhanced drapeability (Lau and Dias, 1994; Heenkenda, 1999). The formability and design capabilities of knitted structures makes them ideal for reinforcements of complex-shaped preforms and has led to their wider acceptance for composite manufacture (Leong *et al.*, 2000; Gokarneshan *et al.*, 2011; De Araújo *et al.*, 2004). However, the loop structure leads to its main disadvantage of distortion during manufacture, resulting in inferior strength and stiffness properties as compared to woven preforms (Leong *et al.*, 1998). As early as 1995, it was noted that knitted-fabric-reinforced composites would not be suitable for highly stressed structures, such as those in aviation, but could be used in car body parts and secondary load-bearing structures (Mayer *et al.*, 1995).

The design capabilities of woven structures are often seen as limited, primarily due to the fixed width restricted by the fixed weaving area. This is influenced by the following factors: weft insertion methods, jacquard harness set-up (for jacquard looms) and the number of permitted headless on the shafts (for dobby looms). There have been limited developments that have allowed for easy movement of the warp to vary the width of the fabric; this concept of fixed width is similar to the restrictions in warp knitting. Weft knitting technology can increase or decrease its dimensions at any point by varying the number of needles in action. The structure can be knitted into its final shape component, eliminating the cutting process after fabric formation and minimising waste.

The various fibre placement methods discussed create a wide scope of fibre orientations, pore geometries, fabric densities and net-shape capabilities. These factors impact the structural performance; therefore, the manufacturing method is integral in producing a product fit for purpose (Ko and Du, 1997).

3D textiles have particularly become a popular choice for composite applications; the following benefits have led to the growth of textile based composites:

- reduced manufacturing costs (high fabrication cost of manual lay-up in traditional composite production is eliminated);
- improved through thickness strength;

Table I.
Possible fabric architectures for different construction processes

Construction process	Dimension	Examples of fabric architecture
Non-woven	1D	Roving yarn
	2D	Non-woven mat
	3D	3D moulded non-woven
Braiding	2D	Biaxial, lace braid
	3D	Multi-axial 3D braid
Weaving	2D	Plain, tri-axial, multi-axial
	3D	Multi-layer, orthogonal, angular interlock
Knitting	2D	Plain weft/warp knit
	3D	Spacer structure

Construction process	Pros	Cons	Properties of fabric
Braiding	Excellent for cylindrical components due to the production of continuous linear material Can be draped around complex shaped mandrel Capable of braiding non-continuous cross-sections, either hollow or solid Cost effective technique for wide range of composite preforms	Fabric width and preform size is limited	Excellent shear resistance High energy absorbing capability
Weaving	High production speeds 2D weaving machines can be easily adapted to produce 3D fabrics Various weft insertion methods to allow curved edges Advances in jacquard mechanics and motors permits variable shedding geometries, and when combined with appropriate weft insertion methods, tailored net-shape preforms can be produced	Fixed maximum width Slow machine set-up due to warping process	Provides the highest strength and stability High dimensional stability High yarn packing density Increased resistance to impact damage High compressive strength in 3D woven
Knitting	High drapeability/formability and extensibility Can form to complex shapes Variable widths achieved through shaping capabilities Quick and easy changes to yarn selection	Loop structure can lead to slight distortion of fabric during manufacture of composite High curvature of yarns results in reduction in mechanical properties, such as reduced in-plane stiffness and strength Lower fibre volume fraction compared to woven	High elastic behaviour (dependent on appropriate selection of yarns) Good energy absorbing characteristics

Table II.
Pros and cons of each construction process, and their properties

- high strength-weight ratios as compared to traditional materials such as metals;
- textiles unaffected by severe conditions (i.e. temperature or weather), making them ideal for civil engineering applications; and
- manufactured in complex shapes.

3D textiles can also be used for soft good applications without being converted to a composite, ranging from small medical devices (e.g. synthetic implant device), to car seat interiors and whole-piece apparel garments. Brown (2005) highlights medical uses of 3D fabrics, particularly a complex woven structure as a vascular draft intended to redirect blood flow in the body.

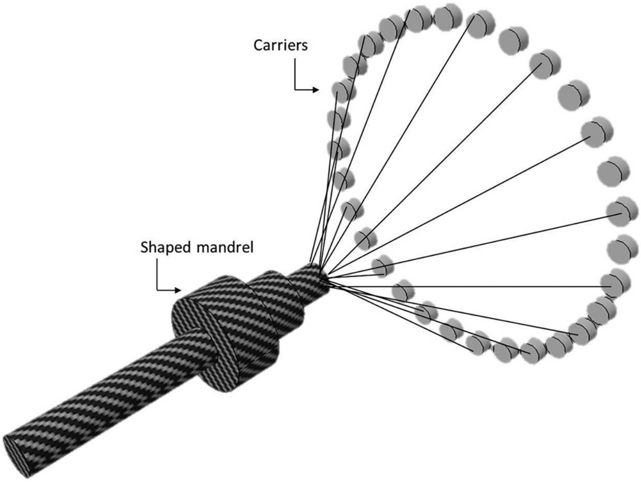


Figure 1.
Braiding over a shaped mandrel

3. Developments in braiding technology for three-dimensional preforms

Braiding manufacturing techniques have developed over the years; however, the fundamental principal of intertwining two or more yarns has remained the same (Kamiya *et al.*, 2000), with yarns interlacing with one another over a wide range of angles from 10° to 85° of the main product axis (Kyosev, 2015; Potluri *et al.*, 2003). Braiding was the first textile process used to manufacture 3D fibre preforms for composites (Mouritz *et al.*, 1999), where it demonstrated its potential for producing lightweight composite components.

The main principle to the braiding process is that two or more sets of yarn carriers (bobbins) rotate along a track in opposing directions, resulting in yarn interlacement at an angle bias to the machine axis. The yarns are thread through bobbins, which travel in a predetermined path, creating a braided pattern. Design capabilities of braiding technology is limited by the width of the machine, with high costs added if large widths are required (Heenkenda, 1999).

Braiding serves a broad range of applications – from ropes and electrical cables to medical items, bicycle frames and industrial tubes (Kyosev, 2015; Branscomb *et al.*, 2013). Yarn interlacement can also occur directly over a shaped mandrel to enable complex shaped composites to be produced (Potluri *et al.*, 2003). Mandrels serve as a mould to support the intertwined yarns and determine the internal geometry of the structure. In some instances, the mandrel forms part of the final component (Potluri *et al.*, 2003). Strong (2008) outlined that mandrels have been used as linings in high-pressure tanks containing fuel. When removal of the mandrel is needed, it is made to be soluble, collapsible or inflatable (Baker *et al.*, 2004).

Braiding has a number of advantages over competing processes such as weaving. Braiding is a flexible process, where structures can be produced as flat fabrics with a continuous selvedge, or as tubular forms with the ability of branching to produce complex shapes, whilst maintaining fibre continuity (Potluri *et al.*, 2003). The braiding process can also produce holes without losing yarn continuity, with greater stability than machined holes (Bannister, 2001).

Braiding is considered 3D when at least three yarn systems are used (Wendland *et al.*, 2015). 3D braiding has the ability to produce complex shaped preforms and complete components such as tubes with T, I and J cross-sections, as compared to 2D braiding. However, 3D braiding machines are slow and expensive (Potluri *et al.*, 2003; Abounaim, 2011); the multi-axis 3D braiding technique is yet to be made fully automated and is still in the early stages of development (Bilisik *et al.*, 2015). The multi-axis technique consists of yarns oriented in various directions and planes, creating multiple layers and enabling zero delamination (Bilisik, 2013).

The reduction in weight in braided reinforced composites is a significant factor that makes braiding technology ideal for car components and influences further research in the automotive industry (Bilisik *et al.*, 2015). Braided composites, as an alternative to heavy metals, can create structural components such as beams and connecting rods; the significant reduction in vehicle weight improves fuel efficiency and emission rates, making car manufacturers seek this technology.

Braided composites have also become a popular choice for sporting equipment, particularly due to their lower costs and reduced weight. Munich Composites GmbH and designer Benjamin Hansbauer used the braiding technique to develop a bicycle preform made from carbon fibre. The braided sleeve is manufactured on a near-net-shape contoured core, with fibre continuity around the entire shape to form the frame of the bicycle (JEC Composites Magazine, 2012). Traditional bicycle frames are manufactured out of a prepreg, where fabrics are cured in tubular shapes that then need to be joined together – a labour-intensive method. However, the braiding technique allows for fully automated fibre lay-up, resulting in higher precision, lower costs and better reproducibility. Munich Composites GmbH also developed braided preforms for hockey sticks, whereby the braiding technique solved fibre wrinkling and allowed the curved shape to be made in a highly automated process (Black *et al.*, 2016).

Zeng *et al.* (2005) obtained numerical and experimental data on the energy absorption of 3D carbon braided composite tubes when altering the dimensions of the tube. The inner radius and thickness of the tubes, as well as the braid angle were varied to characterise the energy absorption properties when these parameters are changed. A main finding, to be expected, was that when the thickness of the tube wall increased, the energy absorption also increased as there was an increase in fibre to share the energy load. Fangueiro *et al.* (2006) investigated the effect of braid angle and reinforcement fibre on the tensile properties of braided composites. The research tested the viability of the composites to be used as a substitute for metal as reinforcement rods in concrete. The braided composites with carbon as the reinforcement fibre repeatedly achieved the highest modulus of elasticity compared to other reinforcement fibres of glass, polyethylene and sisal that were tested. This means more force is needed on the carbon reinforced samples to deform the material. The braided samples were compared with commercial steel rods, and the carbon braided rods were found to have higher ultimate stress, but the modulus of elasticity was significantly lower. The modulus of elasticity is an important parameter in civil engineering applications, which would need to be increased to compete with commercial steel components. The addition of inlay yarns within the braided structure could contribute in achieving higher tensile properties.

Although the yarn interlacement of straight yarns in braiding provides structural integrity for high performance applications, the maximum width and cross-section of 3D braided preforms are limited (Bilisik *et al.*, 2015) and cannot compete with the dimensions that weaving and knitting machines can achieve. The alternating yarn paths in braiding are concepts that could be transferred to warp insertion within knitted structures. This would create a twisting action of the warp yarns around knitted loops, causing a locking effect with minimum yarn shearing, potentially improving mechanical strength.

4. Developments in weaving technology for three-dimensional preforms

Traditionally, weaving is characterised as the interlocking of perpendicular yarns to create a 2D structure (Chen *et al.*, 2011). However, over the years, the complexity of woven designs has increased with the possibility of producing 3D structures. 2D woven flat panels have been used for a number of years for composite applications (Kamiya *et al.*,2000), where panels are layered upon one another until the desired thickness is achieved. However, the lack of through-the-thickness reinforcement limits impact resistance and causes delamination between layers. As an alternative, 3D structures that contain a through-the-thickness yarn that binds layers at varying angles are being used (Chen *et al.*, 2011), such as angle interlock and orthogonal structures. This alternative method for producing composites with substantial thickness eliminates the labour-intensive manual lay-up of individual fabric layers.

A limitation to the use of woven structures in composite applications is the inherent crimp produced during the interlocking of yarns (Badawi, 2007), which reduces overall strength. However, orthogonal structures exhibit significantly high in-plane stiffness and strength due the layers of straight yarns with zero crimp. The yarns are arranged perpendicularly to one another in the X, Y and Z directions, as shown in Figure 2.

Multi-axis 3D weaving allows for the insertion of reinforcement bias yarns oriented in directions other than 0° and 90° to the fabric directions, such as ±45° and ±60° (Labanieh *et al.*, 2015), and was introduced by Ruzand and Guenot (1994). The bias yarns provide substantial improvements to conventional woven preforms, whereby the in-plane properties are improved (Bilisik, 2012). In recent years, prototypes for 3D multi-axis weaving have been developed to characterise the preform properties and to improve the different techniques for producing such fabric (Labanieh *et al.*, 2015). Labanieh *et al.* (2015) used a guide block technique, whereby a rotating feeding unit positions the bias yarns transversely along the *y*-axis for each weaving cycle. This technique was further investigated to identify the influence of the presence of bias yarns on the mechanical properties of composites (Labanieh *et al.*, 2015). 3D multi-axial preforms with bias yarns (yarns in the ±0° to the bias direction) were compared with 3D orthogonal structures. Both were impregnated with epoxy resin by vacuum infusion process. Such findings include lower and non-linear response to tensile testing in the

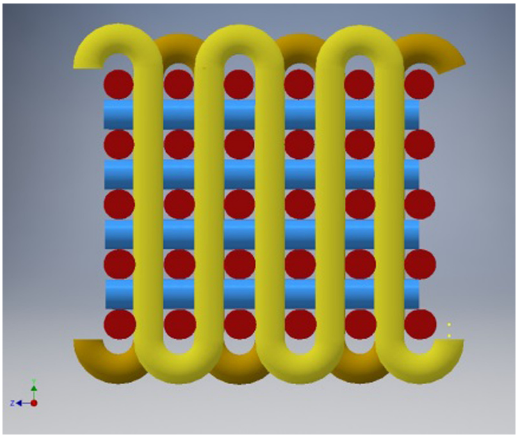


Figure 2.
Side view of orthogonal woven structure

bias direction for the orthogonal structure, compared to the multi-axial structures, which required much higher stress for lower strains.

It is possible to produce woven spacer structures through the traditional velvet weaving technique, whereby pile yarns connect two sets of warp yarns that are woven as separate layers (Deshpande *et al.*, 2013). Dresdon University of Technology have further developed woven spacer structures with the use of woven cross-link fabrics rather than pile yarns for the connection of the outer layers, as shown in Figure 3 (Mountasir *et al.*, 2016); the advancement provides improved mechanical properties for composite applications. Mountasir *et al.* (2016) describe how three warp systems (all in the 90° direction) are needed to produce this structure: one warp system is used during the cross link while the other two systems form floats on the top and bottom of the fabric. A terry weaving mechanism is also needed with the purpose of releasing the temporarily stored fabric length after the completion of the cross-link layer.

Liu *et al.* (2017) investigated the tensile properties of 3D woven hollow sandwich composites of E-glass fibre, composed of upper and lower panels connected by pile yarns. The structure is similar to the knitted spacer fabrics mentioned previously. The pile yarns act as the core connecting material and are woven into the upper and lower panels, forming an integral structure, as shown in Figure 4, with high delamination resistance.

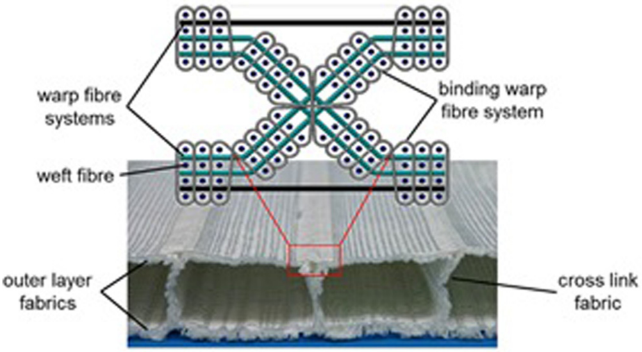


Figure 3.
3D spacer structure made of multi-layered woven fabric (Mountasir *et al.*, 2016, by the kind permission of M Löser)

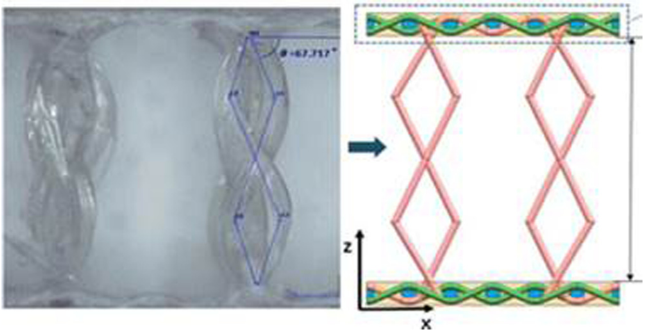


Figure 4.
Structural unit of 3D woven hollow integrated sandwich composites (Liu *et al.*, 2017)

Their study focused on testing the tensile properties in the weft and warp directions, using the results to create theoretical prediction software. The theoretical and simulated data closely matched the experimental results. The warp direction had superior tensile properties compared to the weft, attributed by less crimp in the warp direction.

The concept of separate warp systems working separately to one another could be translated to warp insertion in knitting, where adjacent warps interlock with knitted loops in opposing directions, i.e. alternatively interlocked in the face and back of the fabric. This would create a more isotropic structure, and balance out the reinforcement characteristics in all directions of the fabric.

The manipulation of thread spacing in woven fabrics has enabled developments in shape weaving. This has allowed shaped material forms to be produced instantaneously on the weaving machine, without the need of additional seams. When yarn spacing is increased, better moulding properties are gained due to the ability of yarns to shear out of line (Buesgen, 2015). The traditional take up beam is replaced with a programmable take-up mechanism, which can vary the take-up tension of individual warp ends. Such technology has been used to produce seamless helmet reinforcements which are then transformed into a hard-shell composite.

5. Developments in knitting technology for three-dimensional preforms

Knitting is the most flexible fabric-forming technology, it can manipulate and control individual yarn placement (through holding, transferring, tucking and floating of stitches), making it ideal for controlling directional mechanical properties for particular load situations. Either warp or weft knitting techniques can be used, with weft knitting using either circular or flatbed machines. However, weft flat-bed knitting has the greatest versatility in terms of patterning and loop structure combinations, due to the individual movement of needles (Pamuk and Ceken, 2008). Knitted loops allow for freedom of movement of the yarn and “the tensile properties of knitted structures are influenced by this yarn movement, as the yarns try to change shape from loop form to straight line” (Heenkenda, 1999). However, once the knitted structure becomes a composite, the movement of yarn is restricted and the tensile properties become stable.

It is believed the first application of weft knitting for composites was by Marvin (1961), to produce fashioned conical shapes for the aircraft industry. Since then, many researchers have developed knit structures for composite use, but the low load-bearing properties have rendered use to research level with minimal commercialisation of such technology (Padaki *et al.*, 2006). The company “Preform Technologies” has recently developed shaped carbon fibre preforms that require no extra fabrication or cutting methods, such as T-shaped tubes (Hunter, 2017). The developments will allow for manufacture of carbon fibre reinforced products in automotive, aerospace and marine applications.

Ciobanu *et al.* (2011) described there being three categories of 3D knitted fibre architectures. Multi-axial (warp), spacer fabrics and shell-knitted fabrics using spatial fashioning. Spatial fashioning is a technique, whereby the knitting process takes place on a variable number of needles on each course (Ciobanu *et al.*, 2011).

In recent years, the use of these techniques has been used to develop 3D knitted structures for medical, protective and structural applications (Pereira *et al.*, 2007; Liu *et al.*, 2012; Abounaim and Cherif, 2012). Prior to shaping techniques, fabrics would be draped and stretched to fit the desired shape, resulting in fabric deformation across the structure with reduced fibre volume in given areas. However, the use of advanced manufacturing techniques can create shaped structures with balanced geometries (Power, 2004).

Heenkenda's(1999) study found that an interlock structure essentially constructed of two rib configurations joined together, is suitable for applications requiring high strength, whereas rib structures are suitable for products needing high elastic behaviour. The interlock yarn configuration draws similarities to spacer fabrics where the two outer faces are connected by the spacer yarn.

Spacer fabrics contain yarns in the *x*, *y* and *z* directions, as schematically shown in Figure 5. They can be used in industries such as transport, sportswear, medical and apparel. Their applications range from upholstery and helmet linings, to shoe inserts, bra padding and ballistic vest linings (Davies, 2011), with improvements to weight reduction and fabric breathability. Spacer fabrics are commonly designed to provide cushioning, air flow and moisture flow (Kanakaraj and Anbumani, 2007), particularly for mattress toppers and seat cushions. To maintain the space between the two face layers yet allow compression and resilience, monofilament yarns are typically used as the spacer yarn (Anand, 2016). The outer faces are knitted with elastomeric yarn, which shrinks and contracts the width of the fabric when taken off the machine. This shrinkage causes the monofilament spacer yarn to be pushed into the *z* direction, creating the space between the two face layers.

The use of knitted spacer structures as an alternative to neoprene for knee braces was considered by Pereira *et al.* (2007). Dimensional analysis showed spacer structures offered lower bulk density than the commercial neoprene knee braces, which could provide significant improvement to an athlete's performance. Ye *et al.* (2008) established similar results when studying warp knitted spacers for comfort applications.

Anand (2016) observed that knitted spacer structures exhibit close to isotropic behaviour in terms of breaking loads, tenacity and breaking extension. These properties tend to be considerably weaker in the bias direction for standard knitted and woven fabrics because of the scissoring effect of the structure. The spacer structures, however, have similar values for these properties in the machine direction, cross-direction and 45° direction (Anand, 2016). Near isotropic characteristics are beneficial to composites, whereby the structures properties are easier to predict and the performance behaviour will be the same in any orientation and direction.

The design principals of spacer structures have been used to create 3D preforms of multiple fabric layers connected together. Costa *et al.* (2002) used flat weft knitting technology to create a preform for an airplane wing and consolidated the structure by resin transfer moulding (RTM) to create the composite, as shown in Plate 1. The research concluded that 3D textile preforms for composites allow structural integrity due to the continuity of the preform (manufactured in one piece with no seams); they highlighted that the continuity of preforms reduces operation time and avoids wastage of fibre (Costa *et al.*, 2002). Spacer structures with connecting plane layers rather than pile yarns provides wider scope for thickness dimensions and design possibilities.

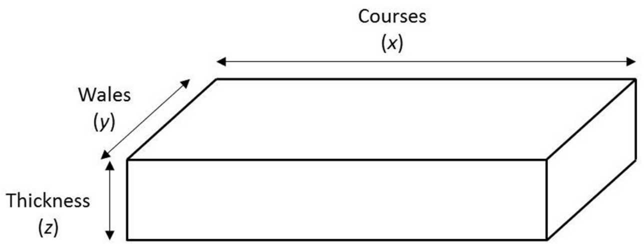


Figure 5.
Schematic of 3D knitted spacer structure, showing *x*, *y* and *z* directions in comparison to the wales and courses

Plate 1.
Knitted preform using spacer structure principals, and composite wing after RTM (Costa *et al.*, 2002)

5.1 Addition of reinforcement yarns to knitted structures

Distortion of knitted structures is a common problem for technical applications. To overcome this, researchers have inserted straight reinforcement yarns in the weft, warp and diagonal directions to create a combined "knit-weave" structure, whereby the ability to drape and mould to complex shapes is maintained. The insertion of inlays in the wale and course directions (using warp and weft insertion respectively) create biaxial knit structures (Hasani *et al.*, 2016). Since the development of this, it has been claimed the addition of floats and inlay yarns can improve the in-plane properties such as strength, resistance to deformation and directional reinforcement of knitted composites (Leong *et al.*, 2000; Ciobanu, 2011; Dev *et al.*, 2005). The addition of inlay yarns increases the fibre content for knitted structures as there is a higher volume of fibre in a given area. This enables higher stiffness and strength properties to be achieved because there is a higher percentage of fibre distributing the loading force, matching the properties of non-woven and woven structures, which typically achieve high fibre content of above 60 per cent (Heenkenda, 1999). Higher fibre content can also be achieved by decreasing the stitch length of the knitted structure (Heenkenda, 1999). Reinforcement yarns also serve the purpose of limiting elongation of the structure, proving crucial for applications, where the initial shape needs to be maintained (Cherif, 2016).

There has been limited research of combining interlocking with interlooping within 3D contoured structures. Shima Seiki was the first to provide a fully automated knitting machine, known as the Lapis, which incorporated warp insertion (Knitting Industry, 2009); however, its lack of commercialisation has prevented researchers from using the machine to identify its potential for technical purposes and shaping capabilities. Current commercial spacer structures that provide thickness to a material lack the integration of inlay yarns in the warp direction, which can offer improved dimensional stability and reduced fabric deformation.

Li *et al.* (2015) identified that the tensile properties of knitted spacer structures can be improved when reinforced yarns are inserted in the weft direction. It can be assumed that the tensile properties would further improve if the structure was combined with warp insertion.

Abounaim (2011) investigated the process developments of manufacturing 3D knitted spacer fabrics for technical textile applications, particularly for use in lightweight construction. Various 3D shapes were developed via flatbed knitting, with some samples containing reinforcement yarns, including that in Plate 2. Tensile testing was carried out to determine how the different integration techniques of the reinforcement yarn affected the tensile properties of the yarn and the end composites. The findings found that when the reinforcement yarn is used as an inlay in either the weft or warp direction, there is only a 5-10 per cent loss in the yarns tensile properties, as compared to a 70 per cent loss when the yarn is used as knitted loops. The sample with only weft inlay as the reinforcement achieved the highest tensile modulus when tested in the course direction; similarly, the sample with only warp insertion achieved the highest modulus when tested in the wale direction. The addition of tuck stitches also had a positive effect on the tensile properties; however, overall, the integration of reinforcement yarn (in any configuration) had a bigger impact on the warp directional properties.

Although warp knitting has less design capabilities as weft knitting in terms of 3D shaping, the technology is also capable of introducing laid-in yarns, which may not be knittable. The laid-in yarn is trapped between the loops and underlap of the warp knitted structure and does not need to interact with the needles. Where warp knitting lacks in design flexibility it exceeds in production rates as it is the fastest method of converting yarn into fabric.

There is a long history of the use of pipes as structural elements in buildings, bridges and automotive applications. Manufacturers have sought to use textile composites for pipes due to their higher strength and lower weight properties (Hashmi, 2006), an important factor when considering the cost and ease of installation. Typically, braiding is the obvious choice for cylindrical structures; however, Pamuk (2014) investigated the potential of knitting tubular preforms for pipe structures using different types of fibre (Plate 3). The study analysed knitted fabric-reinforced pipes made from untwisted multi-filament carbon (UMC), untwisted multi-filament Kevlar (UMK) and twisted Kevlar (TK). The results concluded that the UMC sample was the most sensitive to impact, with the UMK receiving the least damage after impact. Although tensile strength is typically lower for untwisted yarns, in the case of composite manufacture, it is beneficial to have untwisted yarn as it makes it easier for resin penetration, and provides higher linear density and fibre weight fraction. Therefore, the UMK sample showed better performance than the TK sample.

Plate 2.
Flat knitted multi-layer reinforced curvilinear 3D spacer fabric (Abounaim, 2011, by the kind permission of Md. Abounaim)

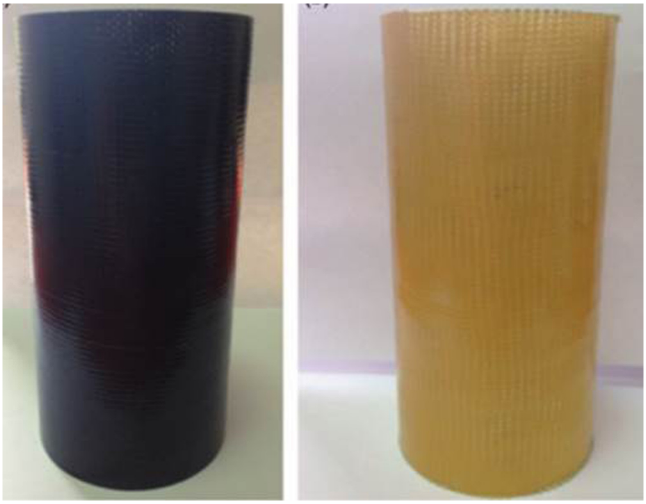


Plate 3.
Carbon and Kevlar composite pipe (Pamuk, 2014, by the kind permission of G Pamuk)

The untwisted yarns also take up more space in the fabric creating less space for an impactor to penetrate through gaps of the knitted loops. The addition of weft and warp insertion would further reduce such gaps and minimise the potential of piercing through the material. This research area could be further developed by adding warp and weft insertion to reduce gaps between the knitted loops, minimising the potential for external objects to pierce through the material. Haller *et al.* (2006) previously investigated this concept for use in construction applications.

Haller *et al.* (2006) developed fully fashioned biaxial weft knit structures as reinforcements in timber joints to avoid critical failures (Plate 4), which are often caused by stresses perpendicular to the grain of the wood. The simplest biaxial knitted structure, shown in Plate 4, was composed of reinforcement yarns in the weft and warp directions; it was transformed into a composite through RTM. The findings from Haller *et al.* (2006) proved that knitted textiles show high potential for reinforcement in engineering applications, particularly as results proved that maximum load tripled and stiffness strength doubled when the wood was reinforced with the biaxial knit structure.

Muralidhar *et al.* (2012) characterised the flexural and impact behaviour of textile composites made from laminates of knitted and woven preforms stacked together. The

Plate 4.
Surface view of plain Jersey with warp and weft insertion; spiral disc of biaxial knitted reinforcement; and placement of reinforcement in wooden test specimen (Haller *et al.*, 2006)

composite achieved higher impact strength when the knitted preforms were placed on the outside with the woven preforms in the middle. The research shows similarities to Hu *et al.* (2010), who investigated composites structured with outer woven layers with two inner weft knitted layers, stitched together with Kevlar yarns, similar to that schematically shown in Figure 6. Contrary to Muralidhar *et al.* (2012) findings, Hu *et al.* (2010) suggested mechanical properties were superior when the woven layers were on the outside. The outer woven layers would transmit stress waves along the fabric plane, while the knitted structures in the core would enable large amounts of energy to be absorbed in the thickness direction. The combination of woven with knit structures enables the different yarn configurations to work together within one material and enhance the scope of mechanical properties. The stitching process can reduce mechanical properties by fabric damage; however, it is a cost-effective way to create a 3D preform that is both strong and energy absorbent. This concept can be translated to warp insertion in knitted structures, whereby inlay yarns would transmit stress waves along the fabric plane, while the knitted loops would absorb impact energy.

6. Experimental

Biaxial knit structures of glass fibre have been produced using a warp insertion device attached to a Shima Seiki SES 122F E5 weft knitting machine. The use of warp inlay yarns in weft knitted fabrics are not commercially available due to the high cost of machinery; therefore, this research has been conducted to identify the viability of warp insertion on standard machinery, and initial testing has characterised the tensile properties of the wale and course directions with warp and weft inlays respectively.

6.1 Materials

A device was developed for warp insertion, which would allow yarns to be interlocked between the stitches parallel to the wale direction. The concept was analysed on a hand dubied knitting machine, as seen in Figure 7, before being transferred to the electronic machine where yarn guide units were used to hold the warp inlay yarn taut, as seen in Figure 8. The positioning of the device on a centre yarn feeder rail allowed yarn feeders to pass behind and in front of the warp inlays; this ensured the inlay was interlocked between stitches forming behind and in front of it.

The warp yarns enter the side of the machine, due to the closed carriage cam box, and travel parallel to the needle beds before being delivered down to the knitting zone. Weights apply tension to the warp yarns below the knitting zone.

Glass fibre, with breaking strength of 0.65 N/tex, was selected for both the ground knitted yarn and the inlay yarns due to its low cost, availability on the market and mechanical properties – particularly its inextensibility (Haller *et al.*, 2006; Balea *et al.*, 2014). The use of two needle beds created a channel for the weft inlay to be inserted, while all

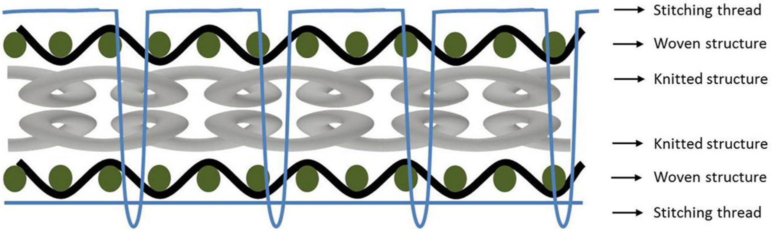


Figure 6. Schematic of a 3D stitched woven-knitted structure

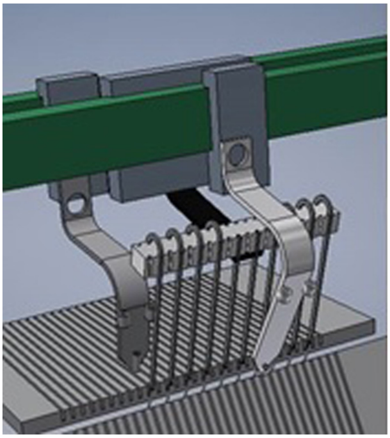


Figure 7.
CAD drawing of warp insertion device on hand machine

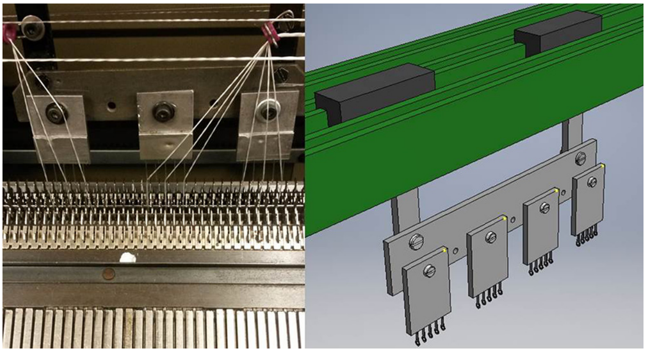


Figure 8.
Warp insertion device on electronic machine, and CAD drawing of device

needles were inactive. A plating feeder was used to insert the weft inlay lower in the needle beds, which prevented the yarn catching on needles.

A hybrid structure with a combination of single bed stitches and full cardigan configuration was developed, as shown in Figure 9. The use of tuck stitches maintained the width of the fabric so that the weft inlay would remain taut, hence restricting extensibility and improving dimensional stability. To provide stability and prevent distortion of the fabric, courses of single bed stitches on every other needle were

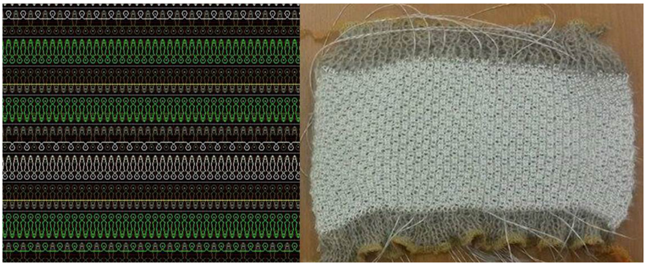


Figure 9.
Yarn path notation and image of hybrid knit structure with weft and warp inlays

intermittently introduced to the full cardigan structure. Without this, there was displacement of wales from tuck stitches pushing stitches away from their normal position, creating high distortion.

The weft and warp inlays are visibly shown in Figure 10; it is noticeable that the warp inlay interlocks above and behind the knitted loops.

6.2 Tensile testing

Tensile tests were performed in the course and wale directions, with and without inlay yarns, following standard BS EN ISO 13934-1:2013 with sample dimensions of 50 × 200 mm. The constant rate of extension was 100 mm/min, with a gauge length of 200 mm and pretension of 0.5 N. Details of samples tested are listed in (Figure 11), the diagrams indicate the direction of testing in relation to the inlay yarns.

6.3 Results

The typical force-strain curves from the samples listed in Figure 11 are shown in Figure 12. Each peak in a curve indicates failure within the fabric, as either the knitted loops breaking beyond their full extension or the inlay yarns breaking after bearing the maximum load. As expected, for both directions, the max load was achieved at lower nominal strains when inlays yarns were present. The straight yarn, unlike the knitted loops, is unable to deform,

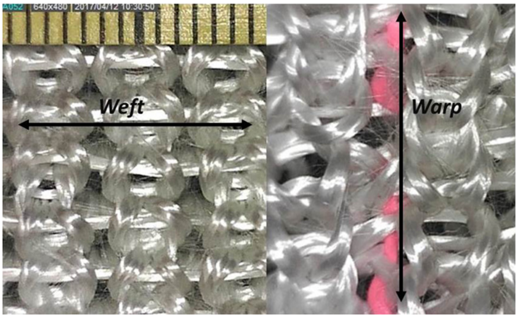


Figure 10. Indication of weft and warp inlays

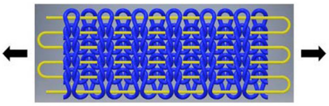
Code	Number of inlay yarns	Direction of test	Number of samples tested	Schematic drawings indicating direction of tensile test in relation to knitted loops and inlay yarns
NWA (No warp insertion)	0	Wale	4	
WA (Warp insertion)	6	Wale	3	
NWE (No weft insertion)	0	Course	4	
WE (Weft insertion)	16	Course	4	

Figure 11. Details of samples tested

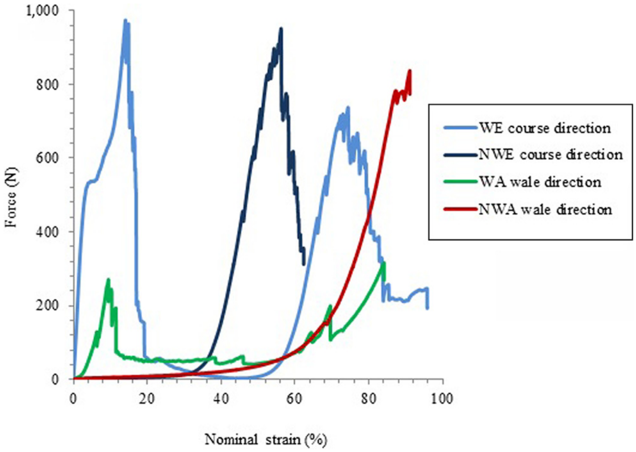


Figure 12.
Force-strain graph of samples WE, NWE, WA and NWA

so instead, it bears the load until the fibres break. Regardless of inlay yarns, the wale direction deforms at lower force; this is due to the restriction in the course direction from the tuck and float stitches. This is shown by NWA sample exhibiting higher strains before failure as compared to the NWE sample. There is sliding at the yarn contact points in the wale direction (Dusserre and Bernhart, 2015), allowing for deformability, but once the stitches are fully jammed, the load increases exponentially where the behaviour is linear up to failure of the fabric.

When warp inlays were inserted (WA sample), each inlay was loaded and failed progressively. Following this, the stitches took the load until further failure of the fabric. The course direction which had 16 weft inlay yarns achieved higher maximum load (for the breakage of the inlays) than the wale direction, which had six inlay yarns (shown by comparison with WE and WA in Figure 12). These results are consistent with those of other studies (Dusserre and Bernhart, 2015) and suggest that a higher number of inlay yarns increases the maximum load, as there is more yarn to share the initial load. The weft inlays are continuous on a course by course basis, suggesting that yarn continuity also increases maximum load.

The results corroborate with previous work in this field (Balea *et al.*, 2014; Dusserre and Bernhart, 2015), whereby the incorporation of inlay yarns requires higher force to achieve low strains. This is particularly important during resin application in textile composites, where inlay yarns would prevent distortion and maintain the initial shape. Continuity of the warp inlays is not possible; however, the continuity of the weft inlays on a course-by-course basis has aided the increase in maximum force.

7. Conclusion

The paper has shown that the use of textile processes for technical applications has been on the rise, and will continue to grow as it makes improvements to products compared to its metal and plastic counterparts. An overview of existing textile technologies, which can produce 3D structures for composite applications has been provided. The benefits and limitations of various construction techniques including their mechanical performance have been highlighted. The need to combine current concepts to create alternative material forms that have unique mechanical properties such as high strength with good mouldability has been noted.

Furthering Abounaim's (2011) research of integrating reinforcement yarns in knitted structures will be a key area of interest in the near future. This will allow for preforms of almost any 3D shape to be produced instantaneously with reinforcement yarns. It has been proven that the introduction of inlay yarns increases fibre content and improves tensile properties; therefore, further research in this area will enable such structures to compete with woven and braided counterparts for composite applications. It has been found that crimp reduces tensile properties, so minimising the crimp factor of the reinforcement yarns through knitted loops would be ideal. This may cause difficulty during weft insertion, as the width of most knitted fabrics tend to contract when taken off the machine, with the straight weft inlay yarn maintaining its original length causing a high crimp factor. The weft inlay yarns would have to be pulled tight after fabric formation to restrict extension in the weft direction, and an additional process to secure these on the side would need to be undertaken. Alternatively, a knitted structure with high stability and minimal stretch, such as "full cardigan" configuration would need to be used to prevent contraction of the width of the structure.

Knitting technology is a diverse and flexible manufacturing method, which is likely to see further growth and development, particularly as an option for lightweight soft and hard composites.

References

Abounaim, M.D. (2011), "Process development for the manufacturing of flat knitted innovative 3D spacer fabrics for high performance composite applications", PhD, Dresden University of Technology.

Abounaim, M.D. and Cherif, C. (2012), "Flat-knitted innovative three-dimensional spacer fabrics: a competitive solution for lightweight composite applications", *Textile Research Journal*, Vol. 82 No. 3, pp. 288-298.

Anand, S.C. (2016), "Three-dimensional fabric structures, part 2 - three-dimensional knitted structures for technical textiles applications", in Horrocks, A.R. and Anand, S.C. (Eds), *Handbook of Technical Textiles*, Woodhead Publishing, Cambridge, MA, pp. 305-332.

Annis, P.A. and Quigley, J.R.T.W. (1998), "Flexible textile composite microscopy", in Summerscales, J. (Ed.) *Microstructural Characterisation of Fibre-Reinforced Composites*, Woodhead Publishing Limited, Cambridge, MA, pp. 17-54.

Badawi, S.S. (2007), "Development of the weaving machine and 3D woven spacer fabric structures for lightweight composites materials", PhD, Dresden University of Technology.

Baker, A., Dutton, S. and Kelly, D. (2004), *Composite Materials for Aircraft Structures*, American Institute of Aeronautics and Astronautics, Reston, VA.

Balea, L., Dusserre, G. and Bernhart, G. (2014), "Mechanical behaviour of plain-knit reinforced injected composites: effect of inlay yarns and fibre type", *Composites Part B: Engineering*, Vol. 56, pp. 20-29.

Bannister, M. (2001), "Challenges for composites into the next millennium—a reinforcement perspective", *Composites Part A: Applied Science and Manufacturing*, Vol. 32 No. 7, pp. 901-910.

Bannister, M.K. (2004), "Development and application of advanced textile composites", *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, Vol. 218 No. 3, pp. 253-260.

Bilisik, K. (2012), "Multiaxis three-dimensional weaving for composites: a review", *Textile Research Journal*, Vol. 82 No. 7, pp. 725-743.

Bilisik, K. (2013), "Three-dimensional braiding for composites: a review", *Textile Research Journal*, Vol. 83 No. 13, pp. 1414-1436.

Bilisik, K., Karaduman, N.S. and Bilisik, N.E. (2015), "Applications of braided structures in transportation", in Rana, S. and Fangueiro, R. (Eds), *Braided Structures and Composites: production Properties Mechanics and Technical Applications*, Taylor and Francis, Milton Park.

Black, S., Sloan, J. and Dawson, D. (2016), "JEC World 2016, the full report", *Composites World*, 29 March 2016, available at: www.compositesworld.com/articles/jec-world-2016-the-full-report (accessed 4 January 2017).

Branscomb, D., Beale, D. and Broughton, R. (2013), "New directions in braiding", *Journal of Engineered Fibers and Fabrics*, Vol. 8 No. 2, pp. 11-24.

Brown, S. (2005), "Textiles: fibre, structure, and function", in McQuaid, M. (Ed.), *Extreme Textiles*, Cooper-Hewitt Museum, New York, NY.

Buesgen, A. (2015), "Shell three-dimensional woven textiles", in Chen, X. (Ed.) *Advances in 3D Textiles*, Woodhead Publishing Limited, Cambridge, MA.

Chen, X., Taylor, L.W. and Tsai, L.J. (2011), "An overview on fabrication of three-dimensional woven textile preforms for composites", *Textile Research Journal*, Vol. 81 No. 9, pp. 932-944.

Cherif, C. (2016), *Textile Materials for Lightweight Constructions*, Springer, Berlin.

Ciobanu, L. (2011), "Development of 3D knitted fabrics for advanced composite Materials", *Advances in Composite Materials- Ecodesign and Analysis*, INTECH Open Access Publisher.

Ciobanu, A.R., Ionesi, D. and Ciobanu, R. (2011), "Design of fashioning lines in 3D knitted fabrics", *Industria Textila*, Vol. 62 No. 4, p. 198.

Costa, A.N., Novo, C., Correia, N., Marques, A.T., de Araújo, M., Fangueiro, S., Esteves, R.M., Hong, H. and Ciobanu, L. (2002), "Structural composite parts production from textile preforms", *Key Engineering Materials*, Vols 230-232, pp. 36-39.

Davies, A.M. (2011), "Use of knitted spacer fabrics for hygiene applications", in McCarthy, B.J (Ed.), *Textiles for Hygiene and Infection Control*, Woodhead Publishing Limited, Cambridge, MA.

De Araújo, M., Fangueiro, R. and Hong, H. (2004), "Modelling and simulation of the mechanical behaviour of weft-knitted fabrics for technical applications: part III: 2D hexagonal FEA model with non-linear truss elements", *Autex Research Journal*, Vol. 4 No. 1, pp. 25-32.

Deshpande, N., Vasudevan, H. and Rajguru, R. (2013). "Recent trends and developments in the use of woven fabric reinforcements for composite materials", *Proceeding ICIAME*, pp. 17-24.

Dev, V.G., Swarna, A. and Madhusoothanan, M. (2005), "Mechanical properties of knitted composites using glass ply yarns", *Journal of Reinforced Plastics and Composites*, Vol. 24 No. 13, pp. 1425-1435.

Dusserre, G. and Bernhart, G. (2015), "Knitting processes for composites manufacture", in Boisse, P. (Ed.), *Advances in Composites Manufacturing and Process Design*, Woodhead Publishing Limited, Sawston, pp. 27-53.

Fangueiro, R., Pereira, C.G., Jalali, S. and Araújo, M.D.D. (2006), "Mechanical properties of braided reinforced composites".

Gokarneshan, N., Varadarajan, B., Sentil Kumar, C.B., Balamurugan, K. and Rachel, A., (2011), "Engineering knits for versatile technical applications: some insights on recent researches", *Journal of Industrial Textiles*, Vol. 42 No. 1, pp. 52-75.

Haller, P., Birk, T., Offermann, P. and Cebulla, H. (2006), "Fully fashioned biaxial weft knitted and stitch bonded textile reinforcements for wood connections", *Composites Part B: Engineering*, Vol. 37 Nos 4/5, pp. 278-285.

Hasani, H., Hassanzadeh, S., Abghary, M.J. and Omrani, E. (2016), "Biaxial weft-knitted fabrics as composite reinforcements: a review", *Journal of Industrial Textiles*, Vol. 46 No. 7, pp. 1-35.

Hashmi, M.S.J. (2006), "Aspects of tube and pipe manufacturing processes: meter to nanometer diameter", *Journal of Materials Processing Technology*, Vol. 179 No. 1, pp. 5-10.

Hearle, J.W.S. (2015), "Introduction", in Chen, X. (Ed.) *Advances in 3D Textiles*, Woodhead Publishing, Cambridge, MA.

Heenkenda, N.K. (1999), "A study of using weft knitted structures for composites", PhD, University of Manchester.

Hu, J. (2008), *3-D Fibrous Assemblies: Properties, Applications and Modelling of Three-Dimensional Textile Structures*, Woodhead Publishing, Cambridge, MA.

Hu, H., Zhang, M., Fangueiro, R. and De Araujo, M. (2010), "Mechanical properties of composite materials made of 3D stitched woven-knitted preforms", *Journal of Composite Materials*, Vol. 44 No. 14, pp. 1753-1767.

Hufenbach, W., Petrinic, N., Hornig, A., Langkamp, A., Gude, M. and Wiegand, J. (2006), "Delamination behaviour of 3D-textile reinforced composites–experimental and numerical approaches", Conference on Damage in Composite Materials: Non Destructive Testing and Simulation, *Stuttgart*, pp. 1-10.

Hunter, B. (2017), *UK Company Develops New 3D Knitted Carbon Fibre Preforms*, available at: www.insidecomposites.com/uk-company-develops-new-3d-knitted-carbon-fibre-preforms/ (accessed 30 August 2017).

Ionesi, D., Ciobanu, R., Ciobanu, L. and Budulan, C. (2010), "Developments of 3D knitted fabrics", 17th International conference Structure and Structural mechanics of Textiles, *TU Liberec, Liberec*.

JEC Composites Magazine (2012), Braiding allows great look, Vol. 76, p. 14.

Kamiya, R., Cheeseman, B.A., Popper, P. and Chou, T.W. (2000), "Some recent advances in the fabrication and design of three-dimensional textile preforms: a review", *Composites Science and Technology*, Vol. 60 No. 1, pp. 33-47.

Kanakaraj, P. and Anbumani, N. (2007), "3D knitted spacer fabrics and their applications", *Melliand International*, Vol. 13 No. 1, p. 47.

Knitting Industry (2009), "Shima Seiki: LAPIS warp weft hybrid flat knitting machine", available at: www.knittingindustry.com/shima-seiki-lapis-warp-weft-hybrid-flat-knitting-machine/ (accessed 8 February 2016).

Ko, F. and Du, G. (1997), "Processing of textile preforms", in Gutowski, T. (Ed.), *Advanced Composites Manufacturing*, 1st ed., John Wiley and Son, Hoboken, NJ.

Kyosev, Y.K. (2015), *Braiding Technology for Textiles*, Woodhead Publishing, Cambridge, MA.

Labanieh, A., Legrand, X., Koncar, V. and Soulat, D. (2015), "Development in the multiaxis 3D weaving technology", *Textile Research Journal*, Vol. 86 No. 17, pp. 1869-1884.

Lau, K.W. and Dias, T. (1994), "Knittability of high-modulus yarns", *Journal of the Textile Institute*, Vol. 85 No. 2, pp. 173-190.

Leong, K., Ramakrishna, S., Huang, Z. and Bibo, G. (2000), "The potential of knitting for engineering composites—a review", *Composites Part A: Applied Science and Manufacturing*, Vol. 31 No. 3, pp. 197-220.

Leong, K.H., Falzon, P.J., Bannister, M.K. and Herszberg, I. (1998), "An investigation of the mechanical performance of weft-knit milano-rib glass/epoxy composites", *Composites Science and Technology*, Vol. 58 No. 2, pp. 239-251.

Li, X., Jiang, G., Nie, X., Ma, P. and Gao, Z. (2015), "Knitting technologies and tensile properties of a novel curved flat-knitted three-dimensional spacer fabrics", *Autex Research Journal*, Vol. 15 No. 3, pp. 191-197.

Liu, C., Zhou, G. and Lu, F. (2017), "Tensile properties and failure mechanism of 3D woven hollow integrated sandwich composites", *Applied Composite Materials*, pp. 1-13.

Liu, Y., Hu, H., Long, H. and Zhao, L. (2012), "Impact compressive behavior of warp-knitted spacer fabrics for protective applications", *Textile Research Journal*, Vol. 82 No. 8, pp. 773-788.

Marvin, A.W. (1961), "2—some mechanical properties of knitted glass laminates", *Journal of the Textile Institute Transactions*, Vol. 52 No. 1, pp. T21-T25.

Mayer, J., Ha, S.W., Ruffieux, K., Tognini, R. and Wintermantel, E. (1995), "Weft knitted fabrics from carbon fibres: reinforcement structures for a new class of thermoplastic composites", *Melliand English*, Vol. 76, pp. E39-E41.

Mountasir, A., Löser, M., Hoffmann, G., Cherif, C. and Großmann, K. (2016), "3D woven near-net-shape preforms for composite structures", *Advanced Engineering Materials*, Vol. 18 No. 3, pp. 391-396.

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: applied Science and Manufacturing*, Vol. 30 No. 12, pp. 1445-1461.

Muralidhar, B.A., Giridev, V.R. and Raghunathan, K. (2012), "Flexural and impact properties of flax woven, knitted and sequentially stacked knitted/woven preform reinforced epoxy composites", *Journal of Reinforced Plastics and Composites*, Vol. 31 No. 6, pp. 379-388.

Ogale, V. and Alagirusamy, R. (2004), "Textile preforms for advanced composites", *Indian Journal of Fibre and Textile Research*, Vol. 29 No. 3, pp. 336-375.

Padaki, N.V., Alagirusamy, R. and Sugun, B.S. (2006), "Knitted preforms for composite applications", *Journal of Industrial Textiles*, Vol. 35 No. 4, pp. 295-321.

Pamuk, G. (2014), "Development of tubular knitted fabric-reinforced composite pipes", *Journal of Industrial Textiles*, Vol. 45 No. 5, pp. 1-13.

Pamuk, G. and Ceken, F. (2008), "Manufacturing of weft-knitted fabric reinforced composite materials: a review", *Materials and Manufacturing Processes*, Vol. 23 No. 7, pp. 635-640.

Pereira, S., Anand, S.C., Rajendran, S. and Wood, C. (2007), "A study of the structure and properties of novel fabrics for knee braces", *Journal of Industrial Textiles*, Vol. 36 No. 4, pp. 279-300.

Potluri, P., Rawal, A., Rivaldi, M. and Porat, I. (2003), "Geometrical modelling and control of a triaxial braiding machine for producing 3D preforms", *Composites Part A: Applied Science and Manufacturing*, Vol. 34 No. 6, pp. 481-492.

Power, J. (2004), "Knitting shells in the third dimension", *Journal of Textile and Apparel Technology and Management*, Vol. 3 No. 4, pp. 1-13.

Ray, S.C. (2012), *Fundamentals and Advances in Knitting Technology*, Woodhead publishing, Cambridge, MA.

Ruzand, J.M. and Guenot, G. (1994), Multiaxial three-dimensional fabric and process for its manufacture, International Patent WO 94/20658, 15 Sept 1994.

Scardino, F. (1989), "An introduction to textile structures and their behavior", in Cho, T.W. and Ko, F.K. (Eds) *Textile Structural Composites*, Elsevier Science, Amsterdam, pp. 1-26.

Sondhelm, W.S. (2000), "Technical fabric structures- 1. woven fabrics", in Horrocks, A.R and Anand, S. C. (Eds), *Handbook of Technical Textiles*, Woodhead publishing, Cambridge, MA.

Strong, A.B. (2008), *Fundamentals of Composites Manufacturing: materials, Methods and Applications*, Society of Manufacturing engineers, Dearborn.

Wendland, B., Ramaswamy, S., Schäfer, J. and Gries, T. (2015), "Three-dimensional composite manufacturing processes", in Boisse, P. (Ed.) *Advances in Composites Manufacturing and Process Design*, Woodhead Publishing, Cambridge, MA.

Ye, X., Hu, H. and Feng, X. (2008), "Development of the warp knitted spacer fabrics for cushion applications", *Journal of Industrial Textiles*, Vol. 37 No. 3, pp. 213-223.

Zeng, T., Fang, D.N. and Lu, T.J. (2005), "Dynamic crashing and impact energy absorption of 3D braided composite tubes", *Materials Letters*, Vol. 59 No. 12, pp. 1491-1496.

Corresponding author

Natalie Ishmael can be contacted at: natalie.ishmael@manchester.ac.uk