

The potential of knitting for engineering composites—a review

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Abstract

Current literature on knitted composites tends to address the aspects of manufacture and characterisation separately. This paper aims to bring together these two sets of literature to provide the reader with a comprehensive understanding of the subject of knitted composites. Consequently, this paper contains a detailed outline of the current state of knitting technology for manufacturing advanced composite reinforcements. Selected mechanical properties of knitted composites, and some of the predictive models available for determining them are also reviewed. To conclude, a number of current and potential applications of knitting for engineering composites are highlighted. With a comprehensive review of the subject, it is believed that textile engineers would be able to better understand the requirements of advanced composites for knitting, and, by the same token, composites engineers can have a better appreciation of the capability and limitations of knitting for composite reinforcement. This should lead to more efficient usage and expanded application of knitted composites. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The textile industry has developed the ability to produce net-shape/near-net-shape fabrics using highly automated techniques such as stitching, weaving, braiding and knitting. In view of the potential for cost savings and enhanced mechanical performance, some of these traditional textile technologies have been adopted for manufacturing fabric reinforcement for advanced polymer composites. Knitting is particularly well suited to the rapid manufacture of components with complex shapes due to the low resistance to deformation of knitted fabrics [1]. Furthermore, existing knitting machines have been successfully adapted to use various types of high-performance fibres, including glass, carbon, aramid and even ceramics, to produce both flat and net-shape/near-net-shape fabrics. The fabric preform is then shaped, as required, and consolidated into composite components using an appropriate liquid moulding technique, e.g. resin transfer moulding (RTM) or resin film infusion (RFI).

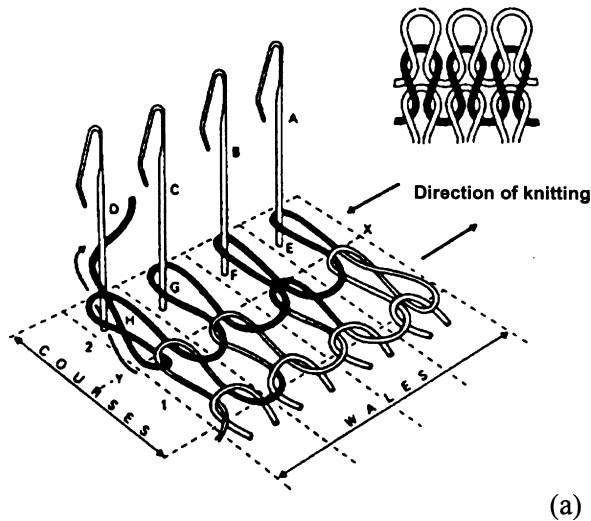
The use of net-shape/near-net-shape preforms is obviously advantageous for minimum material wastage and reduced production time (see, for example, Nurmi and

Epstein [2]). However, the development of a fully fashioned knitted preform can prove time consuming and expensive so that this option could still be economically inefficient overall. In such instances, flat knitted fabrics with a high amount of formability/drapability should be used to form over a shaped tool for subsequent consolidation to produce the required composite component (see, for example, Höhfeld et al. [3]).

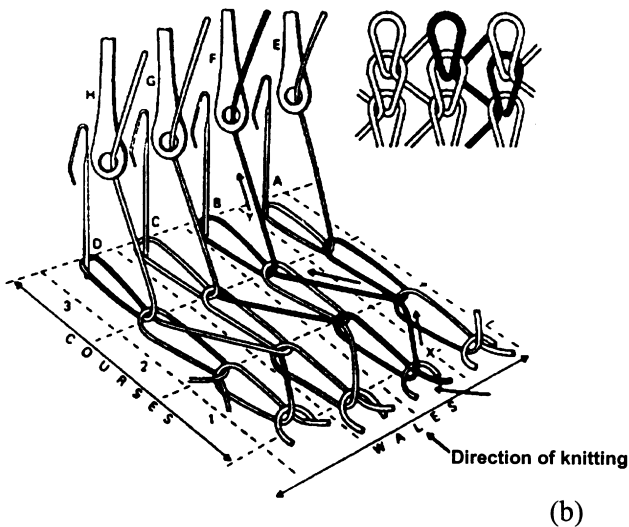
Notwithstanding the exceptional formability, there are serious concerns over the generally poorer in-plane mechanical performance of knitted composites compared with more conventional composites and materials [4–8]. This relative inferiority in properties of knitted composites results predominantly from the limited utilisation of fibre stiffness and strength of the severely bent fibres in the knit structure that afford the fabric to be highly deformable. In addition, damage inflicted on the fibres during the knitting process could also degrade mechanical properties [6].

This paper aims to provide to the reader a general appreciation of the knitting process and the many opportunities it provides for producing efficient fibre reinforcement for advanced composites. Within this objective, the paper first outlines some of the more common types of knitting techniques and machines, and discusses some of the recent innovations to facilitate the manufacture of knitted composites with improved mechanical performance. In this context, the

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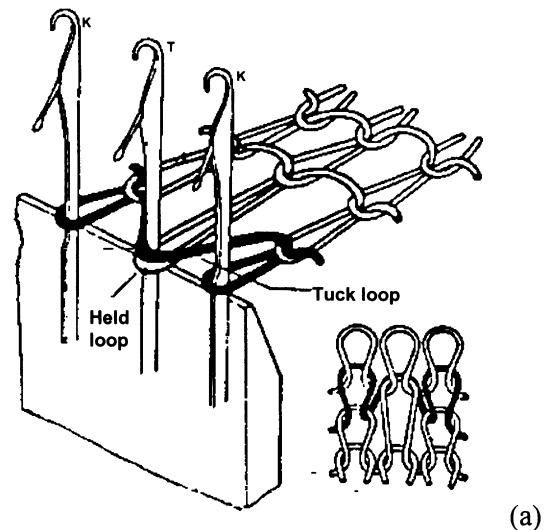
Fig. 1. Schematic diagrams showing the wale and course components of a knitted fabric, and the principles of (a) weft and (b) warp knitting.

performance of advanced knitted composites with respect to mechanical properties such as tension, compression, energy absorption, impact and bearing are reviewed. Analytical and numerical models currently available for predicting stiffness and strength of knitted composites are also presented. Finally, some current and potential applications of knitting for engineering composites are highlighted.

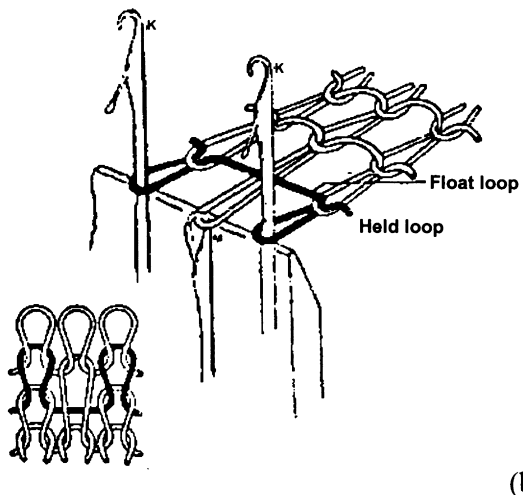
2. The knitting process

Literature on the basics of knitting is widely available, including one by Gohl and Vilensky [9], upon which most of this section of the paper is based.

Knitting refers to a technique for producing textile fabrics by intermeshing loops of yarns using knitting needles. A continuous series of knitting stitches or intermeshed loops



(a)



(b)

Fig. 2. Schematic diagrams showing the (a) tuck and (b) float stitches.

is formed by the needle catching the yarn and drawing it through a previously formed loop to form a new loop. In a knit structure, rows, known in the textile industry as *courses*, run across the width of the fabric, and columns, known as *wales*, run along the length of the fabric. The loops in the courses and wales are supported by, and interconnected with, each other to form the final fabric (Fig. 1).

A wale of loops is produced by a single knitting needle during consecutive knitting cycles of the machine. The number of wales per unit width of fabric is dependent on inter alia the size and density of the needles¹ used as well as the knit structure, yarn size, yarn type, and the applied yarn tension. A course of loops, on the other hand, is produced by a set of needles during one knitting cycle of the machine. The number of courses per unit length of fabric is controlled

¹ The density of needles is more commonly represented by the term 'gauge', which is a measure of needles per unit length in inches.

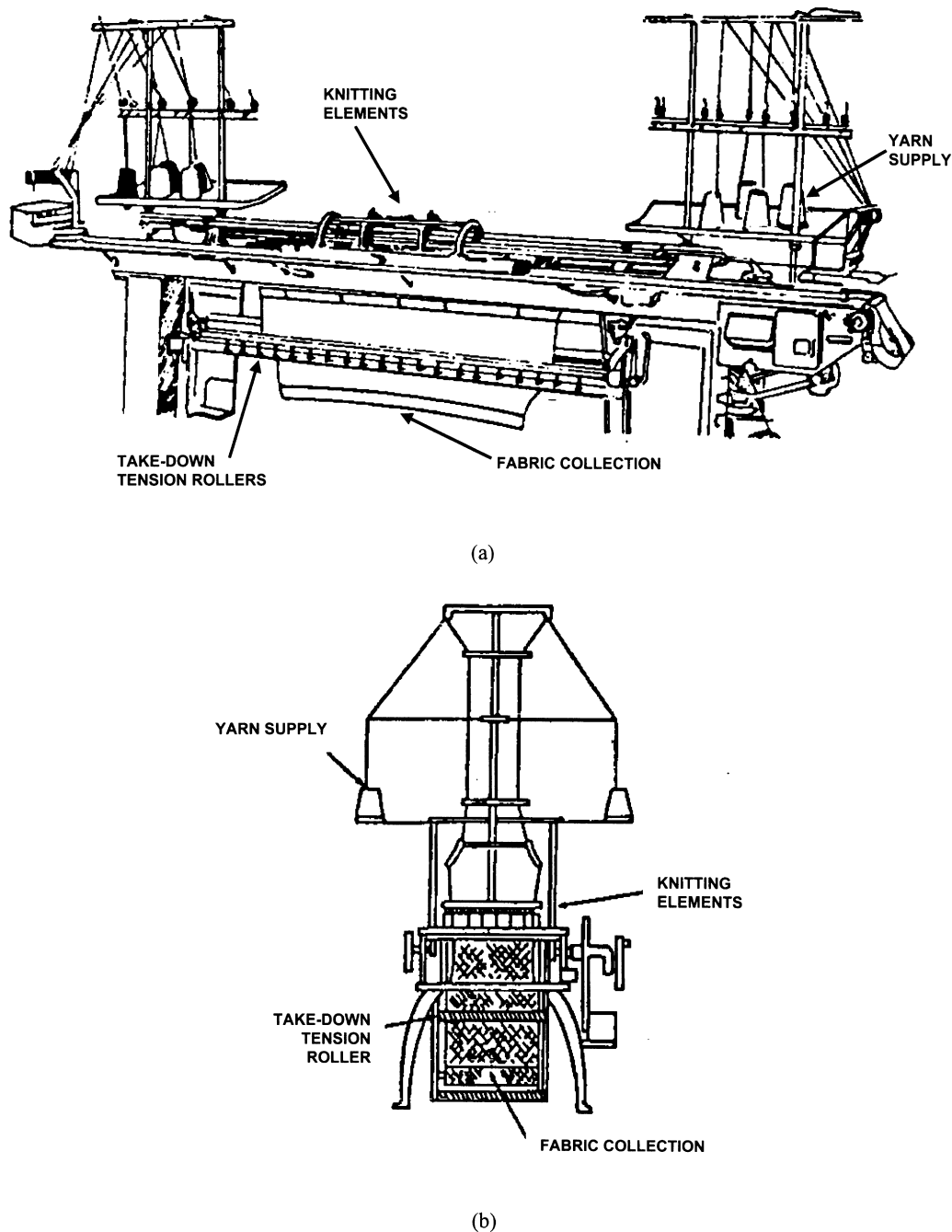


Fig. 3. Illustrations of (a) flat-bed and (b) circular weft knitting machines.

by manipulating the needle (knockover) motion and yarn feed. Standardised tests for measuring and quantifying the number of wales and courses in a unit length of knitted fabric are well documented in the literature [10].

Depending on the direction in which the loops are formed, knitting can be broadly categorised into one of two types—*weft knitting* and *warp knitting* (Fig. 1). Weft knitting is characterised by loops forming through the feeding of the weft yarn at right angles to the direction in which the fabric is produced (Fig. 1(a)). Warp knitting, on the other

hand, is characterised by loops forming through the feeding of the warp yarns, usually from warp beams, parallel to the direction in which the fabric is produced (Fig. 1(b)). More precisely, warp knitting is effected by interlooping each yarn into adjacent columns of wales as knitting progresses. Fig. 1 shows the basic structure of the weft (i.e. plain knit) and warp (i.e. single tricot) knitted fabrics. Generally, weft-knit structures are less stable and, hence, stretch and distort more easily than warp-knit structures so that they are also more formable. It is noteworthy that an obvious advantage of

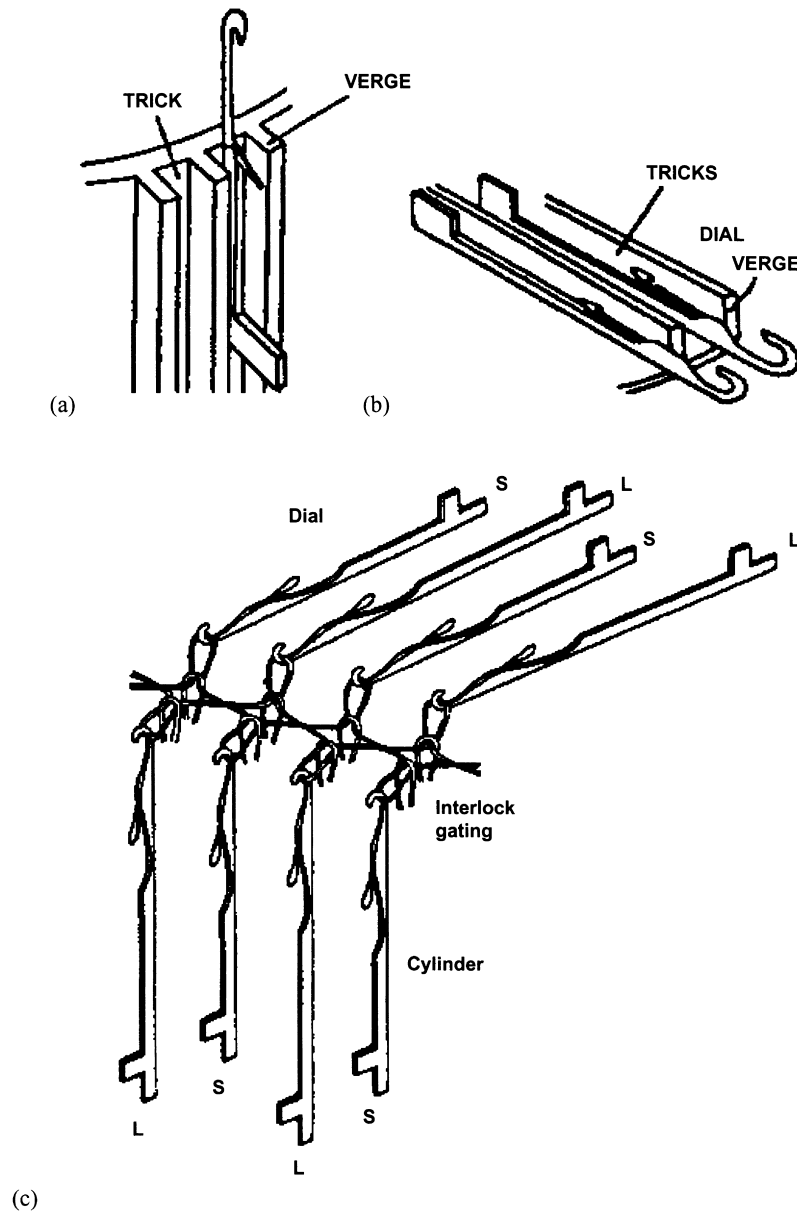


Fig. 4. Schematic diagrams of the (a) cylinder, and (b) dial, needles of a circular knitting machine, and (c) the manner in which they interact to effect the knitting process.

warp over weft knitting is that the former tends to have a significantly higher production rate since many yarns are knitted at any one time. The ease with which weft-knitted fabrics unravel and the cost associated with warping beams are also important considerations in choosing between weft and warp knitting. Clearly, weft knitting is preferred for developmental work whereas warp knitting would be more favourable in large-scale production.

In knitting, *float* and *tuck* stitches/loops (Fig. 2) represent the main routes for modifying knit structures to achieve specific macroscopic properties in the fabric. In general a tuck stitch makes a knitted fabric wider, thicker and slightly less extensible. A float stitch, on the other hand, creates the opposite effect, as well as increases the proportion of

straight yarns in the structure, which is an important consideration for many composites applications.

3. Knitting machines

According to Gohl and Vilensky [9], weft knitting machines may be broadly classified into two types, namely flat-bed and circular, whilst the two most common warp knitting machines are the Tricot and the Raschel.

3.1. Weft knitting

3.1.1. Flat-bed machines

Flat-bed, or flat-bar, machines are characterised by the

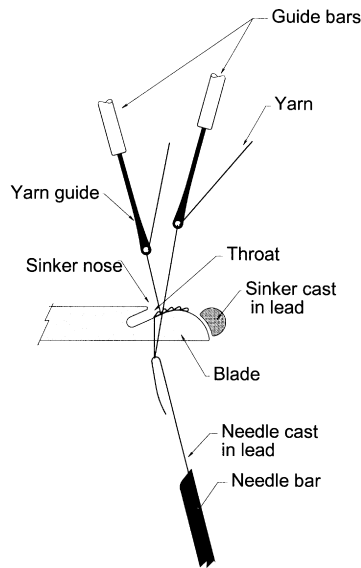


Fig. 5. Schematic diagram showing the relative positions of the guide bars to the knitting needle in warp knitting machines.

arrangement of their needles on a horizontal or flat needle bed (i.e. linear needle arrangement) (Fig. 3(a)). Most flat-bed machines have two needle beds which are located opposite to each other. The motion of the needles during knitting is controlled by cams in the yarn carrier which act upon the butt of the needles as they travel back and forth along the needle bed. This action causes each of the needles to rise and fall in turn to facilitate loop formation of the yarn along the length of the needle bed. It is from this action that the term ‘weft knitting’ is derived. It is noteworthy that flat-bed knitting machines have low production rates since the yarn is knitted back and forth across the needle bed. This results in slight time delays with each direction change that would become significant over an extended period. Flat-bed machines have gauges ranging from 3 to 15 and therefore their fabrics are normally of large loops with low stitch densities.

3.1.2. Circular machines

Circular weft knitting machines may be single- or double-bed and their needles, as the name suggests, are arranged in a circular needle bed (i.e. circular needle arrangement) (Fig. 3(b)).

Single-bed machines have their needles arranged vertically along the perimeter of the circular knitting bed. This set of needles are called *cylinder needles* (Fig. 4(a)). Double-bed machines have an additional set of needles, called *dial needles*, mounted horizontally along the circumference of a dial which in turn sits above and perpendicular to the cylinder needle bed (Fig. 4(b)). The relative positions of the dial needles are so that they are sandwiched between a pair of cylinder needles, and vice versa. In both types of machines, the needles are normally rotated past stationary

yarn feeders to effect knitting. As with the flat-bed machines, the motion of the needles are controlled by cams.

Since with a circular machine the yarn is knitted in a continuous fashion, significantly higher production rates are achieved compared with flat-bed machines. This continuous knitting also means that fabrics produced on circular machines are tubular and contain no seams. Circular machines have gauges ranging from 5 to 40, and therefore their fabrics normally consist of small loops with relatively high-stitch densities.

3.2. Warp knitting

3.2.1. Tricot machines

Tricot machines have only a single needle bar and up to four yarn guide bars to a needle (Fig. 5). The needle bed is straight and occupies the width of the machine. The guide bars essentially move relative to the needles to facilitate interlooping of yarns with adjacent loops as the fabric is knitted. Being typically fine gauge machines, the tolerance between the needles and yarn guides is very fine and therefore Tricot machines are commonly used with multifilament yarns. With the smoothness and regularity in fibre diameter, speedier and relatively problem-free knitting is achieved with these machines. It is noteworthy that the non-stretch characteristics of Tricot knits and thus their relative stability of structure often render them substitutes for woven fabrics.

3.2.2. Raschel machines

Raschel knitting machines may have one or two straight needle beds that occupy the width of the machine. Depending on the knit structure more than 20 guide bars can be used, although the usual number is between four and 10. Due to the greater number of guide bars that a Raschel machine can accept, it is possible to knit an immense variety of structures on these machines. Nevertheless, the basic stitch formation of Raschel knits is the same as for Tricot knits.

Since Raschel machines usually have more guides fitted to them than Tricot machines, they are coarser gauge machines too. The coarser tolerance between the needle and yarn guides means that spun yarns can be knitted. It is noteworthy that Raschel has become the generic name for describing fabrics knitted on a warp knitting machine with two needle bars. Further, Raschel fabrics generally tend to be characterised by their open mesh, net or lace-like structure, that are usually knitted from spun, rather than multifilament, yarns.

The myriad of knit architectures that are possible with either weft or warp knitting are highlighted by Ramakrishna [11].

4. Fibre damage during knitting

During knitting, fibres are required to bend over sharp radii and manoeuvre sharp corners in order to form the

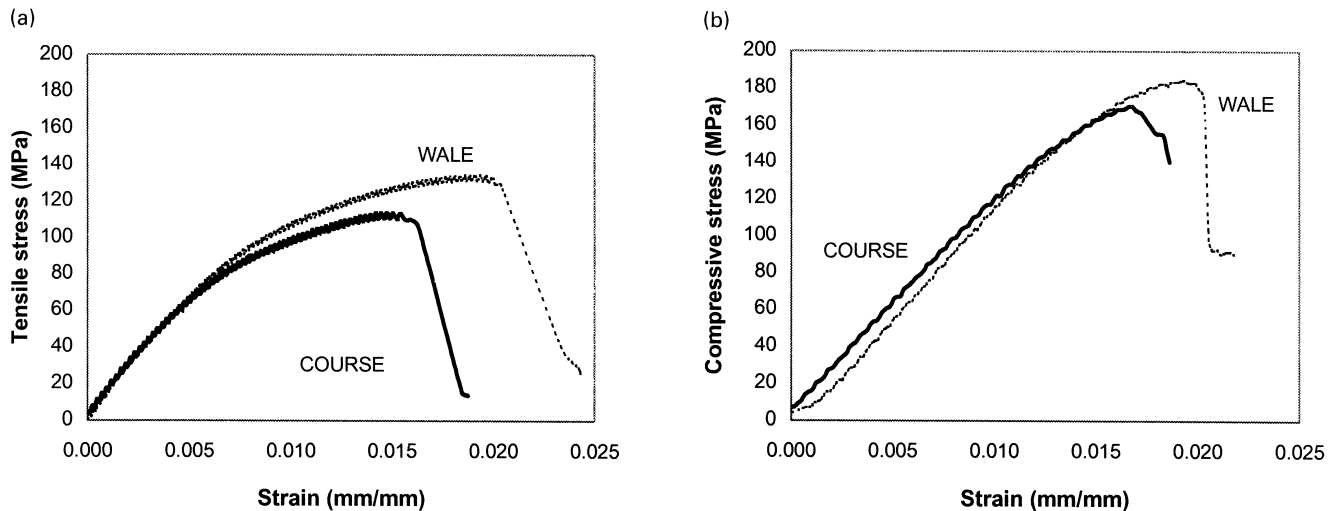


Fig. 6. Typical stress–strain curves of rib-knit composites under (a) tension and (b) compression, loadings [23].

knitted loops of the structure. However, most load-bearing fibres suitable for engineering composites exhibit high elastic stiffness and high dimensional stability [2,12], thus making it difficult to fulfil this requirement without causing significant damage to the fibres. In fact, Lau and Dias [13] found that the loop strength of glass yarns increases almost exponentially with knitting needle diameter. As a result, this limits the choice of structures to relative simple ones and modifications to conventional machines are sometimes also necessary. Concessions such as using ceramic guides with an extension force spring [6] and employing more flexible fibres have proved successful in alleviating the problem of fibre damage, although the latter option tends to compromise the final properties of the composite [14,15]. With advanced fibres, may they be glass [5], carbon [16], or aramid [17], more flexible fibres normally means using spun yarns consisting short fibres (50–100 mm) that are twisted together. In this way, some of the superior properties of the advanced fibres are retained whilst improving on knittability. Incidentally, spun yarns have also been shown to be advantageous for improved wetting properties compared with monofilament yarns [14,15].

Lau and Dias [13] pointed out that when yarns come into contact with knitting elements of the machine, due to friction, the tension in the yarn, T , would build up according to Euler's capstan equation:

$$T = T_i e^{\mu \vartheta} \quad (1)$$

where T_i is the yarn input tension, μ the mean coefficient of friction between the yarn and the knitting elements, and ϑ the sum of the angles between the yarn, needles and other knitting elements in contact with the yarn. Whilst, on the one hand, the superior tensile properties of advanced fibres suggest good knittability, their generally low-rupture strains, on the other, tend to mean that quite large tension build-up in the yarn, which would otherwise be relieved by

more stretchable yarns, such as wool, are also created. As a result, fibre damage due to premature tension failure is also a significant impediment to the knittability of advanced fibres.

Damage to the fibres also arises from abrasion with knitting elements of the machine. Usually only surface filaments in a fibre yarn are fractured in the process which makes the fibres appear hairy or frayed [13]. Through dust emission measurements, Andersson et al. [18,19] showed that the knittability of a fibre or yarn is related to its toughness and surface characteristics, the latter of which can be modified through sizing or lubrication [13]. It should be noted that for advanced composites, the compatibility between the size and the matrix resin warrant serious attention. Chou and Wu [20] showed that fraying increases with the amount of tension exerted on the fibres during knitting and claimed that some degree of fraying, which promotes fibre bridging, could actually enhance composite properties such as tensile strength and impact resistance, albeit only marginally.

5. Mechanical properties

The in-plane mechanical properties of knitted composites are usually anisotropic [6,7,16,21–29] (Fig. 6(a)). This is due to a difference in the relative proportion of fibres oriented in the knitted fabric [16,24], and is therefore a function of the knit structure [6,22,23] as well as knitting parameters, such as stitch density [22,23,30]. The knit structure is not only controlled by the choice of knit architecture but also by the amount and manner to which the fabric is deformed, and thereby modifying the relative fibre orientation prior to consolidation [21,25–28,31,32] (Fig. 7(a)). Similarly, knitted composite properties are also controlled by manipulating parameters such as loop lengths or stitch density of a particular knit architecture [22,23,33] (Fig.

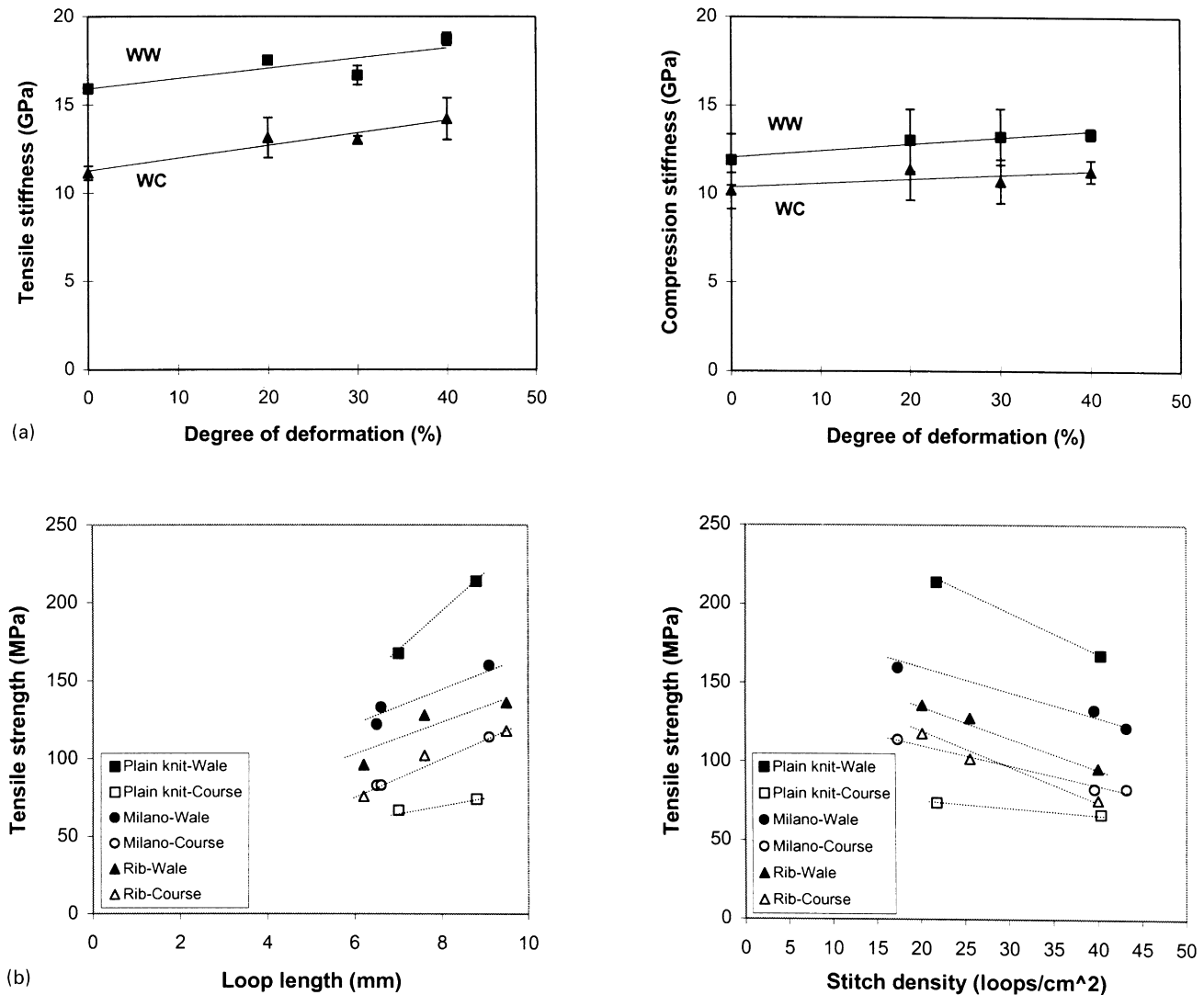


Fig. 7. For a particular knit architecture, the in-plane properties of knitted composites are affected by (a) the amount of deformation in the fabric [31], and (b) the knit parameters of the fabric [33]. (a) Composites with fabric deformed along the wale axis and tested in the wale and course directions. (b) Three different architectures, each knitted to several loop lengths and stitch densities, and tested in the wale and course directions.

7(b)). Leong and colleagues [31], for instance, reported that the tensile stiffness and strength of composites reinforced with Milano-rib knit are enhanced with deformation in the fabric. They [33] also showed that the tensile properties of Milano-rib, plain- and rib-knit composites improve and degrade with loop length and stitch density, respectively (Fig. 7(b)). It is noteworthy that knitted composites are nevertheless much more isotropic under compression than under tension since their compression properties are dominated by those of the matrix [7,21,23,31,33] (Fig. 6(b)). It will be noted from Fig. 6 that, also due to the dominance of the matrix, knitted composites are generally superior in compression than in tension.

Verpoest and colleagues [29] inferred that the in-plane strength and stiffness of knitted composites are inferior to woven, braided, non-crimp and unidirectional materials

with an equivalent proportion of in-plane fibres due to the limited utilisation of fibre stiffness and strength resulting from the severely bent fibres in knit structures. Similarly, knitted composites are also expected to have in-plane properties that are close to those of random fibre mats composites. (Later in the paper, some data are provided in Tables 2 and 3 which illustrate the above statements). Interestingly, there is some evidence which suggests that a knitted composite built up of multiple layers of fabric can exhibit better tension [16,27,28] and compression [7] strengths, strain-to-failure [7,27,28], fracture toughness [34], and impact penetration resistance [35], compared to laminates with only a single layer of fabric. This has been attributed to increased fibre content and/or mechanical interlocking between neighbouring fabric layers through nesting.

The complex nature of knit structures is mirrored in the

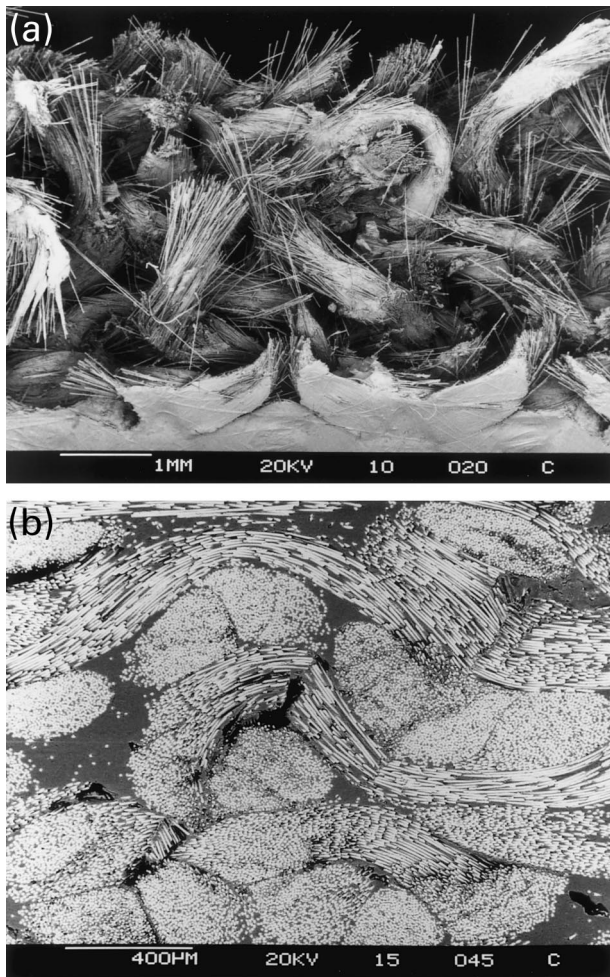


Fig. 8. Representative micrographs showing the fracture modes in knitted composites subjected to (a) tensile and (b) compressive loadings [31]. (a) Fracture of load bearing fibre tows at yarn cross-over points and legs of knitted loops. (b) Euler buckling of a load bearing fibre tow.

failure behaviour of these materials. Under tensile loading, failure usually results from fibre fractures at yarn cross-over points and/or at the side legs of knitted loops, which, respectively, correspond to regions of high stress concentration and planes with minimum fibre content [7,16,22,26,31] (Fig. 8(a)). For a multilayer laminate, ultimate tensile failure is usually preceded by multiple cracking of the matrix [7]. The cracks, which initiate from yarn–matrix debonding [36] and so correspond to the rows and columns of knitted loops in the fabric, develop progressively with loading until a saturation density is achieved before final failure occurs [37].

Under compressive loading, failure is dictated by Euler buckling in regions of minimum lateral support which mainly occur in the plane of the legs of the knitted loops (Fig. 8(b)). The fact that the legs are very often curved rather than straight further promotes buckling, thereby causing the fibres to fracture prematurely [7,21,31]. This buckling, which subsequently causes debonding of the fibres from the matrix, is observed

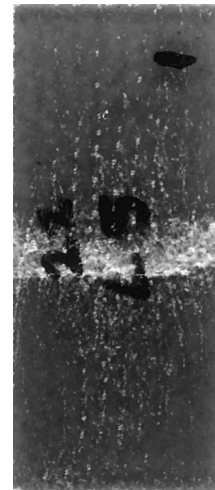


Fig. 9. Example of a failed compression knitted composite sample [31].

macroscopically as parallel rows of matrix cracks running along the loading axis [7] (Fig. 9).

Mechanical properties aside, the curved nature of the knitted loops has its advantage. The highly looped fibre architecture ensures that knitted fabrics are able to easily undergo significant amounts of deformation when subjected to an external force. Their formability raises the potential of knitted fabric for cost-effective composite fabrication of complex and intricate shapes. This advantage extends to permit holes in a composite to be formed or knitted in, instead of drilled. With continuous fibres diffusing stresses away from the hole, the strength in the knitted/formed hole region is increased, thus leading to notch strength [17] and bearing properties [7,8] that are higher than for composites with a drilled hole (see Table 1). Knitted composites have been shown to be generally notch-insensitive where notched strengths are either higher or similar to their unnotched counterparts [17] (see Table 1).

The three-dimensional (3D) nature of knitted fabrics are also effective in promoting fibre bridging to enhance opening mode fracture toughness where improvements of up to $10\times$ and $5\times$ over those of glass prepreg and woven thermoset composites, respectively, have been reported [38,39] (Fig. 10). It is noteworthy that the difference in fracture toughness between a knitted and a woven carbon/thermoplastic composite appears to be less significant [40]. As pointed out earlier, the fracture toughness also improves with the number of fabric layers used in the composite [34]. These superior Mode I fracture toughness values are reflected in the energy absorption capabilities [7,24,41] (as exemplified in Table 2) and impact penetration resistance [42] of knitted composites. It is noteworthy that impact damage appears as a region of dense and complex array of cracks on the impacted surface, whilst on the unimpacted surface, it is characterised by a myriad of matrix microcracks that generate radially from a densely damaged zone (Fig. 11(a)). Consequently, the damage zone takes on a trapezoidal shape (Fig. 11(b)) that is typically observed in

Table 1
Typical notched [17] and bearing [8] properties of knitted and woven composites (in the wale/warp direction)

Property ($W/D = 3$)	Notched			Bearing		
	Knitted aramid/epoxy			Knitted glass/epoxy		Woven glass/epoxy
	Unnotched	Formed	Drilled	Formed	Drilled	Drilled
Strength (MPa)	63	100	61	338	275	369
Strain-to-failure (%)	–	–	–	4.4	3.7	5.1

prepreg laminates [43]. Predictably, the post-impact compression strength of knitted composite laminates decreases with the size of the damage zone, which in turn increases with impact energy [7].

6. Modifications and innovations

6.1. In-lay yarns and float stitches

As mentioned earlier in this paper, the looped nature of the knit structure renders knitted composites inferior as structural materials. Moderate improvements to the strength and stiffness of knitted composites are achievable with the incorporation of float stitches in to basic architectures [5]. Table 3 reveals that tensile properties, for example, are not significantly enhanced with this method since the float stitches carry with them an inevitable amount of crimp.

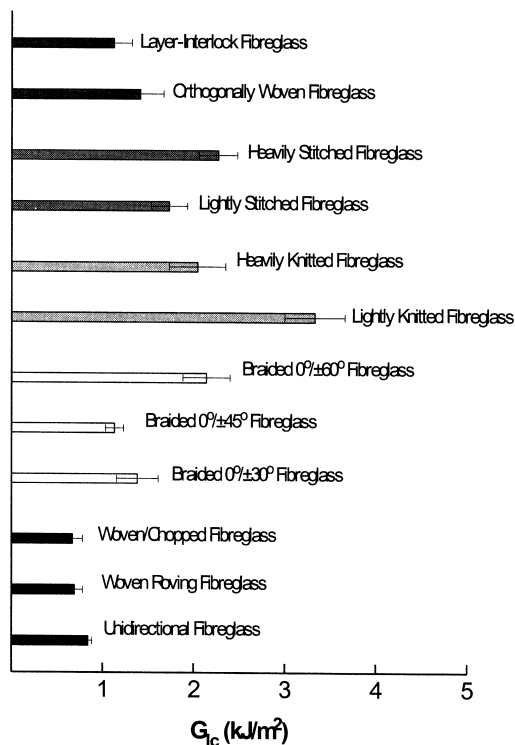


Fig. 10. Comparison of Mode I fracture toughness values for thermoset composites reinforced using different types of textile fabric [39].

A more effective way of enhancing the in-plane properties of knitted composites is by introducing virtually straight, uncrimped fibres into the knitted structure [16,24,41,44–46]. These straight fibres are introduced by insertion into either a weft- and/or warp-knit structure during the knitting process. By so marrying the weaving and knitting processes, the hybrid fabric guarantees an optimum combination of improved mechanical properties (due to the straight fibres) and good forming characteristics (due to the knitting component of the fabric) [12,44]. Further, with inserted yarns, the anisotropy of a knitted composite can also be manipulated to suit a particular requirement (see Table 2). Whilst the tensile strength and stiffness and the energy absorption capabilities of knitted composites are highly dependent on fibre content, Ramakrishna and Hull [16,24,41,46] showed that, at a constant fibre volume fraction, the introduction of in-lay yarns can significantly improve the properties, provided the uncrimped yarns are preferentially oriented.

Weft-insert, weft-knit fabrics (Fig. 12) are produced on flat-bed machines that have the capability of continuously and progressively feeding a straight yarn in to the needle bed just ahead of each knitting action so that the yarn is locked inside the loops (Fig. 13).

More recently, work at Dresden [47,48] has produced a version of multilayer multiaxial weft- and warp-insert weft-knit fabrics. These fabrics were produced using a modified V-bed flat knitting machine which incorporates warp and weft guides/feeders (Fig. 14), in addition to the standard knitting needles, through which uncrimped yarns are introduced into the fabric. Whilst the insertion of off-axis yarns are not yet possible, they are nonetheless theoretically possible to achieve. These multilayer weft-knit fabrics are therefore, in principle, very similar to their warp-knit counterparts (i.e. non-crimp fabrics) (see Section 6.3), and so they are expected to have similar performance. Further, Offermann [48] claimed that **these fabrics have the potential of minimising damage to the uncrimped yarns, and producing fully fashioned preforms** (see Section 6.5). The cost and quality implications of this technique as compared with the non-crimp fabrics is however unclear at this stage.

Alternative to weft-insert, weft-knit fabrics, straight, in-lay yarns can also be introduced into warp-knit structures using Raschel machines [9,45]. A warp-insert, warp-knit fabric has a typical warp-knit structure but between these

Table 2

Comparison of selected mechanical properties for carbon/epoxy composites based on a weft-knit fabric with and without weft inserted in-lay yarns, and a woven fabric [111,112]

Property	Tensile strength (MPa)		Tensile stiffness (GPa)		Specific absorption energy (kJ/kg)	
	Course/transverse	Wale/longitudinal	Course/transverse	Wale/longitudinal	Course/transverse	Wale/longitudinal
Knitted without inlay ($V_f = 20\%$)	29 ^a	60 ^a	11 ^a	15 ^a	17 ^{b,c}	26 ^{b,c}
Knitted with inlay ($V_f = 20\%$)	260 ^a	42 ^a	32 ^a	10 ^b	70 ^b	50 ^b
[0 ₂ /90 ₃] _{ns} crossply ($V_f = 55\%$)	1216	839 ^d	82 ^d	52 ^d	43 ^e	43 ^e
0/90 Woven ($V_f = 50\%$) ^f	625	625	17	17	—	—

^a After Ramakrishna and Hull [16].

^b After Ramakrishna and Hull [24].

^c Values projected from tests conducted on composite tubes having V_f 's of up to 15% (after Ramakrishna and Hull [16]).

^d Values estimated from Rule-of-Mixtures, using unidirectional data from Eckold [111].

^e After Hull [112].

^f After Eckold [111].

wales are laid unlooped yarn with minimum crimp in them. The knitted wales and the straight yarns are connected to each other by means of yarns passing from wale to wale whilst interlacing with the straight yarns, as in weaving, along the way (Fig. 15).

Weft-insert, warp-knit fabrics (Fig. 16) are in principle produced in a way similar to that employed for weft-insert, weft-knit fabrics, except in this case a warp knitting machine is used instead of a weft [12]. These fabrics offer greater flexibility for the type and amount of in-lay fibres that can be used for obtaining an optimum preform in terms of cost and performance [45].

6.2. Split-warpknits

More recently, using the weft-insert, warp-knit technique, strips of thermoplastic film have been co-knitted with load-bearing fibres to produce what are known as split-warpknits (Fig. 17) [12,49–52]. The development of these fabrics is aimed at high speed, high volume production of composite components. Strips of polypropylene (PP) and polyethylene terephthalate (PET) films are used instead of fibres to keep

the cost low and to minimise the amount of induced micro-waviness in the in-lay yarns that arises due to a mismatch in thermal expansion coefficients between the thermoplastic and glass. Consolidation of the fabrics is accomplished by either heating and cooling in one common mould (i.e. single-mould technique), or by preheating in a press and then transferring to a separate cooler tool for forming (i.e. press-mould technique). Depending on the degree of preheating, amongst other things [51], the lower cost press-mould technique could produce composites of inferior mechanical properties (refer to Table 4). The relatively poorer properties are attributed to higher amounts of porosity and resin-rich regions, and less uniform fibre distribution [49]. On the whole, nonetheless, split-warpknit composites have comparable tensile and bending properties to equivalent commingled woven composites, but at only a fraction of the manufacturing cost [49].

The split films were found to create rather large gaps between the straight glass rovings, particularly in biaxially reinforced composites. The size of the gaps is related to the size of the film, which has to be thick enough to ensure sufficient resin for complete impregnation and wet-out of

Table 3

Comparison of selected mechanical properties for glass/epoxy composites based on a weft-knit fabric with and without float stitches, continuous fibre random mat and woven fabric [5,111]

Property ($W_f = 45\%$)	Tensile strength (MPa)		Tensile stiffness (GPa)	
	Course/transverse	Wale/longitudinal	Course/transverse	Wale/longitudinal
Knitted without float stitches ^a	32.3	138.7	7.7	11.8
Knitted with float stitches (1×1) ^a	29.0	70.5	3.4	6.7
Knitted with float stitches (2×1) ^a	67.0	101.1	7.4	9.8
CFRM ^a	177.4	191.9	10.2	10.8
0/90 woven ^b	330.3	330.3	15.6	15.6

^a After Rudd et al. [5].

^b Values estimated from tests conducted on laminates having a V_f of 33% (after Eckold [111]).

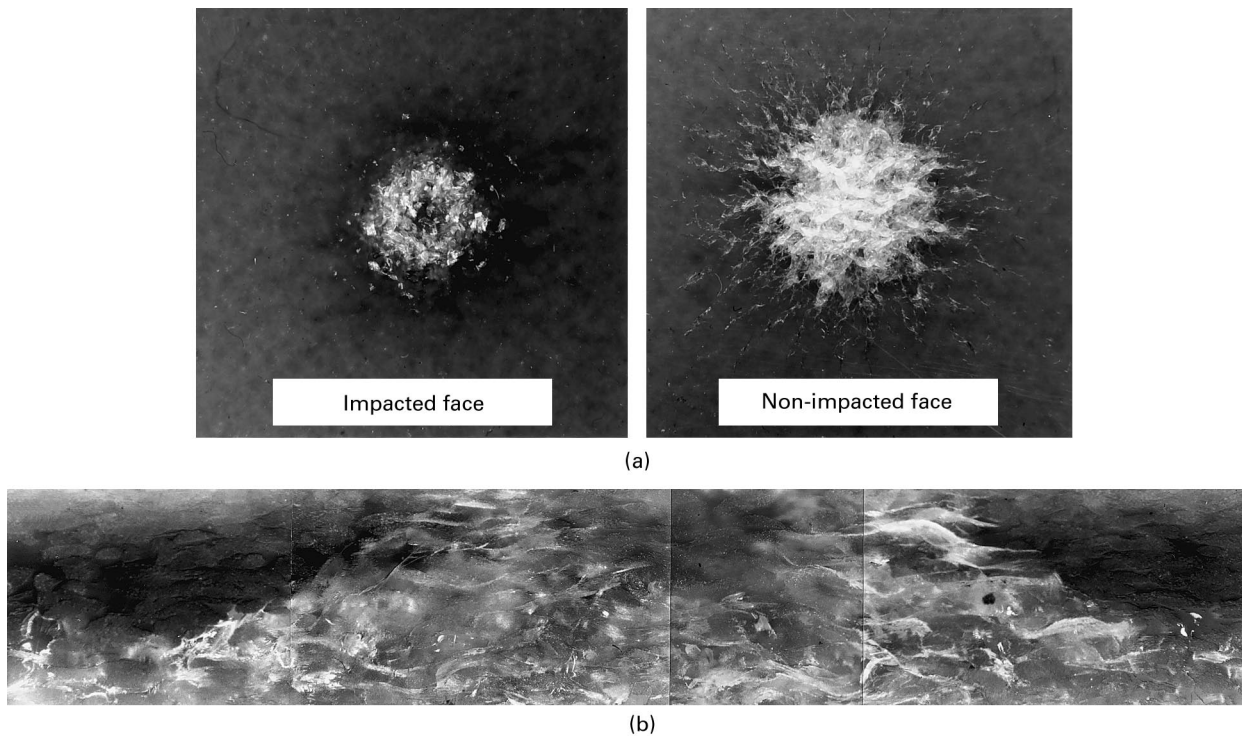


Fig. 11. Representative fractographs of the impact damage zone of a knitted composite [7]. (a) Plan view. (b) Cross-sectional view.

the glass rovings. Whilst stacking the 2D split-warpsplit fabrics could promote nesting between the different layers and hence limit the ‘gap’ problem, it was found to be more effective when a much thinner (polyester) yarn was used as the knitting component in conjunction with a hybrid of glass rovings and split films both being the in-lay components. Not only was the latter technique successful in alleviating the ‘gap’ problem, it also produced fabrics with in-lay yarns that were much straighter and have improved impregnation and wetting characteristics [49].

It is noteworthy that split-warpsplit fabric with multiaxial reinforcements could be produced in principle by using more sophisticated warp knitting techniques discussed earlier in this paper.

6.3. Multiaxial multilayer warp-knit (non-crimp) fabrics

The concept of in-lay yarns can be taken to the other extreme where knitted loops are present only to hold

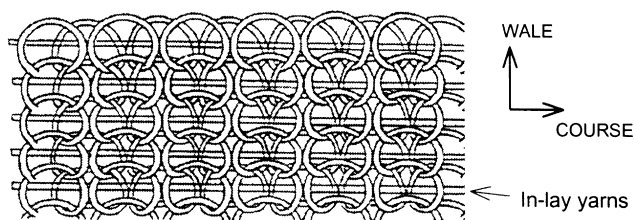


Fig. 12. Schematic of a typical weft-insert, weft-knit fabric produced on a flat-bed weft knitting machine [16].

together uncrimped yarns. Whilst the mechanical properties of non-crimp composites are expected to be considerably better than knitted composites, this is nonetheless achieved with much sacrifice to the formability of knitted composites.

There are three basic systems for producing multiaxial multilayer warp-knit, or non-crimp, fabrics [53]. Firstly, there is the so-called Karl Mayer system. In principle, this is an extension of the weft-insert, warp-knit fabrics described earlier. A rotation action of special mislappng guides are used to insert the in-lay fibre yarns in to the knitted structure, thus making it possible to have off-axis yarns oriented at between 30° and 60° in the fabric [54]. It should be noted that fabrics produced using this technique have a relatively open mesh whereby most part of the in-lay yarns are not supported by the knit component per se [53,55].

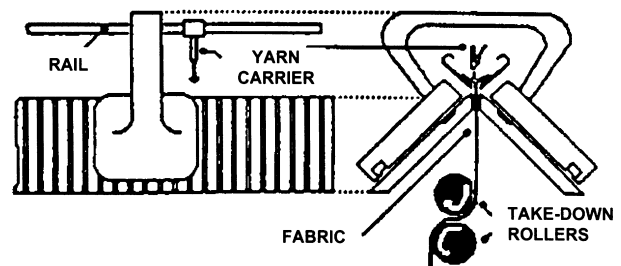


Fig. 13. Schematic diagram showing the general principle of weft-insert weft knitting.

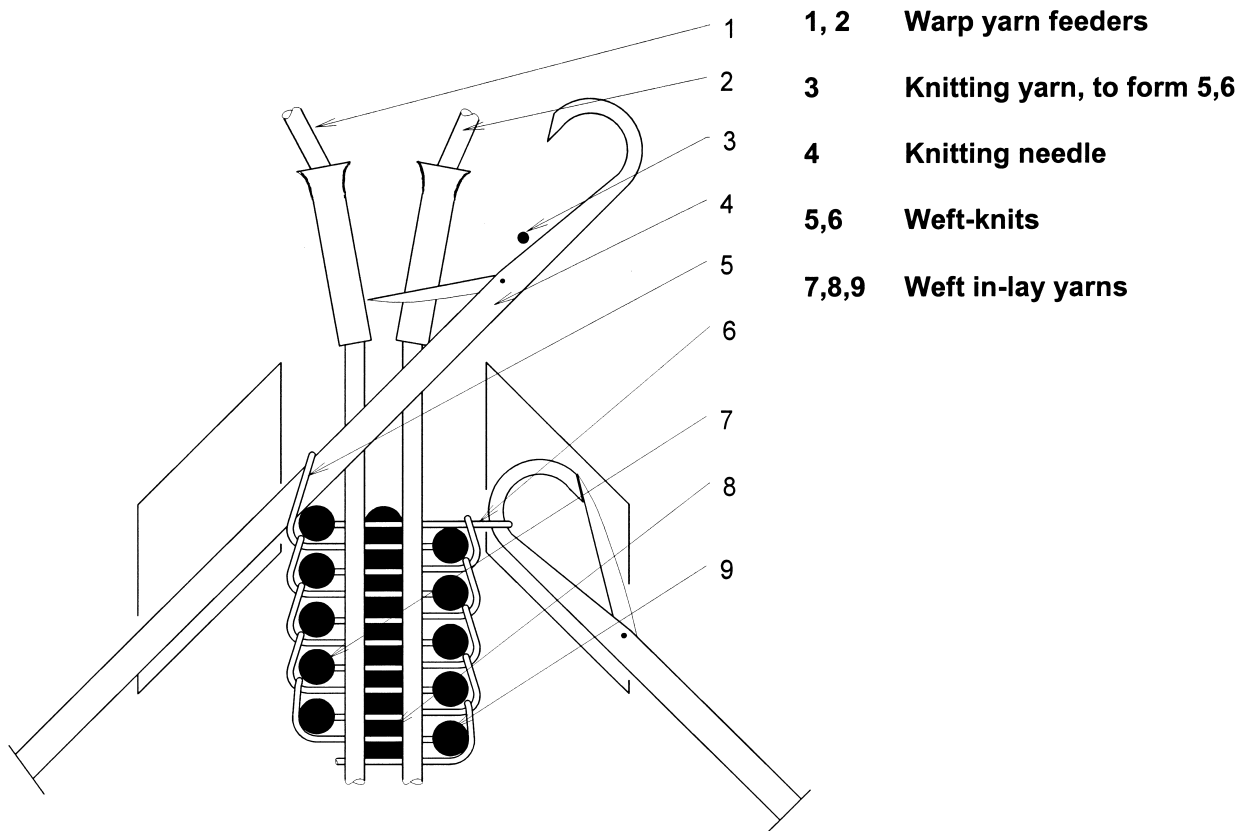


Fig. 14. Schematic of the relative position of the in-lay yarn feeders to the knitting needles in the production of multilayer, biaxial weft-knit fabrics [47,48].

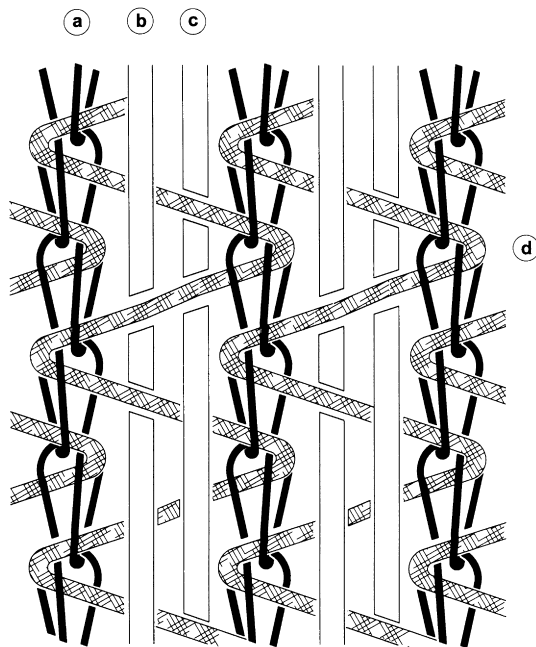


Fig. 15. Schematic of a warp-insert warp knitted fabric produced on a Raschel machine: (a) chain warp stitch; (b) and (c) woven-in yarns; and (d) warp knitted yarn [9].

The other two main systems available for producing non-crimp fabrics are the so-called Liba (Copcentra) (Fig. 18) and Malimo (Maschinenbau) (Fig. 19) systems. Materials produced on the former machines are more specifically referred to as WIMAG (verwirktes multiaxiales Gelege) fabrics whilst those produced on the latter are known as NVG (nälgewirkte variable Gelege) fabrics.

Fig. 18 illustrates a four weft insertion system machine, but higher numbers are possible with larger machines which can also incorporate layers of fleeces or chopped strand mats [55–59]. With the Liba system, reinforcing fibres are drawn from creels and then deposited in the required orientation via a weft insertion mechanism. The weft insertion mechanism comprises yarn carriers that oscillate between the width of the machine during which the fibre yarns are laid down and secured before they are all finally fixed together by means of a warp-knit structure [60]. Apart from 0 and 90°, the orientation of the fibre sheets can be laid down at off-axis angles of 30–60° [55,59,61]. The warp knitting needles are inserted in the thickness direction of the fabric thus exposing the straight fibre yarns to impalement and consequently fibre damage and misalignment [60].

With the Malimo system, a parallel weft sheet of fibres is first of all assembled with the aid of a weft guiding carriage (Fig. 19) [57]. The weft sheet is continuously in transit as fibres are inserted and this causes the fibre orientation to deviate slightly. Depending on the weft density [54],

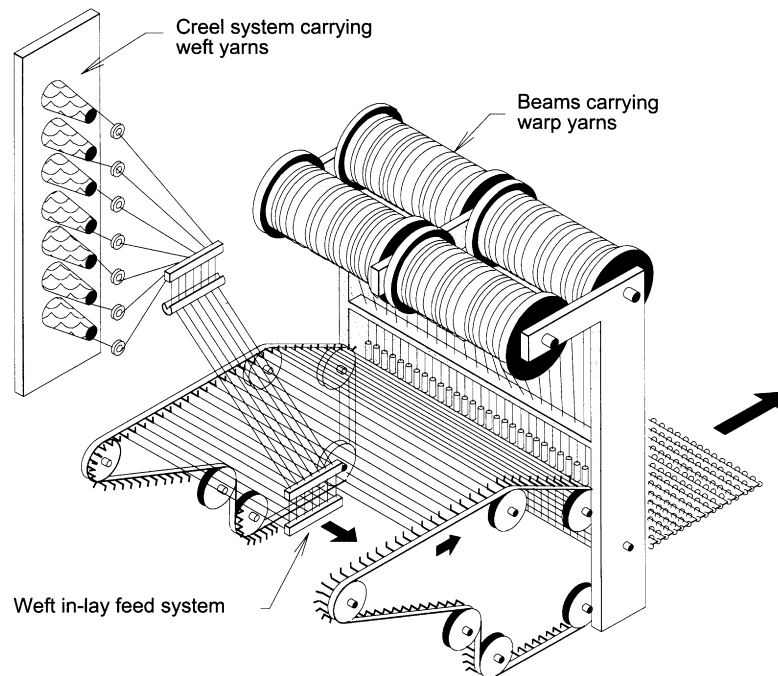


Fig. 16. Schematic diagram showing the general principle of weft-insert warp knitting on a Raschel machine [12].

deviations of 2° – 5° from 90° [59] can occur. The remaining fibres that form the NVG fabric are inserted at angles of 0° – 80° , as required, by means of fibre guiding arms. Incidentally, this fibre guiding mechanism makes precise control of fibre orientation difficult thus introducing typical deviations of between 2° and 8° with respect to 45° [53]. Nevertheless, this mechanism allows a zig-zag and other selective fibre reinforcement patterns to be achieved in the NVG fabrics [59,61]. Paradoxically, the inability of the system to achieve uniform preset fibre orientations produces a more isotropic material than is expected from a more precisely laid up quasi-isotropic laminate. As in the Liba system, the combined layers of fibres are finally held together by means of a warp-knit structure. However, contrary to the Liba system, the Malimo system permits the gaps between

the fibre yarns to be controlled so that the straight fibre yarns are not impaled during knitting/stitch bonding. However, these gaps can promote air entrapment [4] and the formation of large resin-rich areas [60] in the laminates during consolidation. Nevertheless, improved non-crimp fabrics with significantly reduced gap size can now be obtained [62].

Horsting et al. [59,61] reported that the tensile properties and impact damage performance of WIMAG fabric reinforced polymer laminates are superior to laminates reinforced with NGV fabric. Similarly, for concrete samples, WIMAG have higher flexural strengths to NVG [55,57].

It is noteworthy that in the last two systems described, bi-, tri- and quad-axial fabrics of glass, carbon and even polypropylene have been produced using polyester and aramid warp knitting yarns [60,63–65]. The amount of binder used is kept small (to minimise damage and fibre crimp) but sufficient to hold the non-crimp layers for ease of handling of the fabric.

Three main advantages provide the impetus for the development of non-crimp fabrics. Firstly, unlike multilayer woven preforms, the material affords cost-effective off-axis reinforcement. Secondly, like multilayer woven preforms, this material has the potential to greatly reduce production cost through near-net-shaping of the preform, and hence, reduce material wastage and remove the need for laborious laying up [65]. Finally, this material has the potential to outperform traditional 2D prepreg tape laminates since it too contains nominally straight fibres but with the added advantage of having through-the-thickness reinforcement for improved out-of-plane properties. Whilst

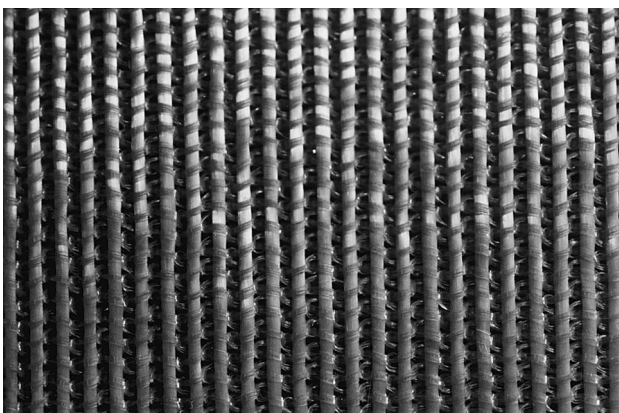


Fig. 17. An example of a split-warpsplit fabric [38].

Table 4

Comparison of selected mechanical properties for composites based on woven fabric, and biaxial split-warps fabric manufactured via different processing routes [49]

Property (V_f in loading direction = 25%)	Single-mould technique		Press-mould technique
	Commingled woven	Split-warps knit	Split-warps knit
Tensile strength (MPa)	390	447	273
Tensile modulus (GPa)	17	18	14
Bending strength (MPa)	324	155	–
Bending modulus (GPa)	14	15	–

stitched 2D laminates can also afford these positive attributes, stitching is nevertheless a secondary operation, and there appears to be a general component size and cost restriction on this technique [66].

In general, 3D non-crimp composites have inferior in-plane properties when compared against unidirectional prepreg tape laminates of similar layup [60,64] (see Table 5). The tension control of the through-the-thickness component is paramount to minimise any out-of-plane crimping (or, “pillowing”) of the in-plane fibre yarns whilst maintaining good handleability of the preform. Similarly, the yarn size and stitch density will determine the degree of in-plane crimping and fibre damage in the load carrying fibre yarns. The presence of any such crimping could render non-crimp composites far less desirable as a structural material than unidirectional prepreg tape composites. Provided the degree of fibre undulation is small non-crimp composites should exhibit superior tensile, compression and flexural properties to comparable 2D woven composites [63,64,67], otherwise the woven composite can still prove superior [68]. On the other hand, insufficient tension in the through-the-thickness yarns will cause them to buckle under cure pressure and, hence, be ineffective at providing a crack closure force.

Given the similarity between non-crimp and unidirectional prepreg laminates in terms of having virtually straight

in-plane fibre yarns, Wang et al. [69] and Bibo et al. [64] have used with some success the Classical Laminate Plate Theory (CLT) to predict stiffness properties of non-crimp composites. The CLT analysis does not account for any through-the-thickness reinforcement and this is acceptable only when the in-plane fibres are not significantly influenced by the knitting yarns. Table 5 gives examples of how the CLT predictions compare with experimentally determined data for a series of triaxial composite laminates.

Fig. 20 shows typical fractographs of a unidirectional prepreg tape and a non-crimp laminate subjected to tensile loading. It appears that the knit structure in the non-crimp composite is effective in constraining delamination and longitudinal splitting that are normally associated with unidirectional prepreg tape laminates [64]. Other than that, it seems that non-crimp and unidirectional prepreg tape laminates have very similar failure mechanisms (i.e. multiple cracking in off-axis plies and delamination at $\pm 45^\circ$ interfaces) [63,69].

The damage generated in non-crimp composites by low energy impact is more complex than that in unidirectional prepreg tape laminates. In plan view, the damage consists of lemniscate or peanut shaped delaminations that resemble a spiral staircase through the thickness (Fig. 21(a)). In addition, a series of parallel matrix cracks, which appears to coincide with the interfibre tow resin-rich

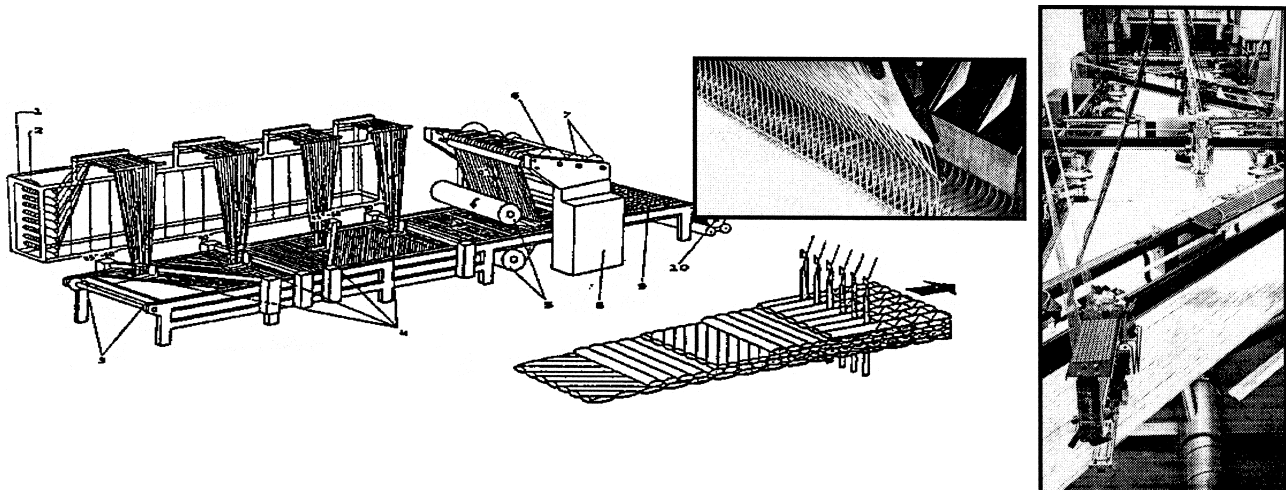


Fig. 18. Schematic diagram depicting the Liba system [57,58].

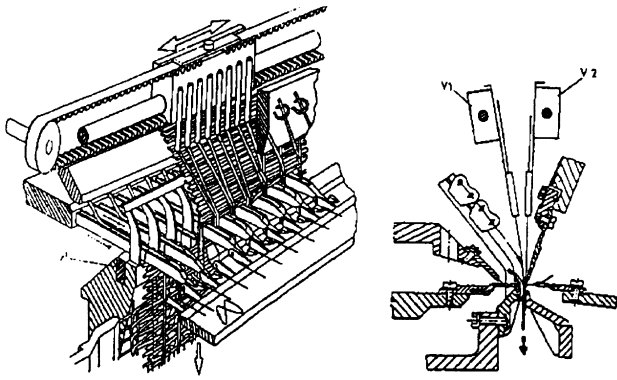


Fig. 19. Schematic diagram depicting the Malimo system [57].

regions, are also created in the damage zone. The presence of through-the-thickness yarns in the non-crimp fabric and stitched material appear to be effective in reducing the amount of back face spalling compared with unidirectional prepreg tape laminates. The level of improvement is linked to the mechanical properties of the through-the-thickness yarn [65].

In the cross-section the formation of damage has been described as having a trapezoidal morphology with the apex originating at the point of impact (Fig. 21(b)). This is characteristic of what is usually observed in unidirectional prepreg tape laminates. However, in the case of non-crimp composites, rather than a collection of shear cracks linking delamination planes, they reveal an intricate array of cracks not dissimilar to that observed in more conventional knitted composites (as described in Section 5 and shown in Fig. 11(b)). The fracture pattern in non-crimp composites may be described as root-like, i.e. cracks are subject to the local terrain and are diverted around tows [65].

Despite an apparent superiority in interlaminar fracture toughness compared with unidirectional prepreg tapes [70–72] due to the knitting yarn acting to bridge (crack shielding) planes of delamination, there was little improvement observed in the suppression of delamination damage due to impact [65]. The damage tolerance of non-crimp and

unidirectional prepreg tape composites is similar [65], although the former exhibits increasingly superior compression-after-impact strengths with impact energy level [65,73].

Attention should be given to the link between mechanical properties and the manner in which the preform and composite are manufactured [60,64]. For example, tensile properties are degraded by the impalement of the non-crimp layers by knitting needles which causes fibre distortion and damage, a phenomenon not dissimilar to that observed for stitched composites [66]. A way to eradicate this is to ensure knitting needles are inserted between tows of in-plane fibres but the gaps are potential resin-rich sites which are detrimental to some properties, particularly fatigue performance. Further, depending on layup, Hogg et al. [63] found that the tensile and flexural performance of laminates with heavier fabrics are inferior to those with lighter ones. More recently, Du and Ko [74], through a geometrical model, highlighted the flexibility of these fabrics by showing the inter-relationship between various preform manufacture parameters, including fibre volume fraction, knit yarn content and in-plane fibre orientation.

The consolidation process chosen for the different composites used in a comparative study is also of utmost significance since the overall microstructure, and hence properties, are influenced by the manufacturing process [75]. This fact is clearly demonstrated in the work of Kay and Hogg [73] where they compared the impact damage tolerance of non-crimp laminates produced from prepreg and hand layup routes with unidirectional prepreg tape laminates.

The influence of knit parameters such as material, tension, architecture and density on mechanical performance appears to have received little systematic attention despite clearly being important [65,76]. Bibo et al. [65], for example, showed that Kevlar knitting yarns produced more impact resistant laminates than polyester yarns. Whilst a whole range of properties—tensile, compression, flexural, interlaminar shear, shear, bearing, impact and post-impact compression—have been evaluated for non-crimp composites

Table 5

Comparison of elastic and strength data for 2D unidirectional prepreg tape [64], 3D non-crimp [64] and stitched 2D uniweave [60] carbon/epoxy laminates of triaxial construction

Test orientation	2D unidirectional prepreg tape [45 ₂ , -45 ₂ , 0 ₆ , -45 ₂ , 45 ₂] _S		3D Non-crimp [{45, -45, 0}, {0, -45, 45}] _S		Stitched 2D uniweave	
	0°	90°	0°	90°	0°	90°
Tensile modulus (GPa)	64.8	21.4	60.8	17.2	68.2	—
Compressive modulus (GPa)	59.9 ^a	19.6 ^a	54.7 ^a	16.5 ^a	60.0 ^b	—
CLT modulus prediction (GPa)	70.0	23.3	63.1	21.1	80.3 ^c	40.0 ^c
Tensile strength (MPa)	951	123	621	159	852	—
Compressive strength (MPa)	852 ^a	215 ^a	574 ^a	236 ^a	640 ^b	—

^a Tests were performed using the IITRI test procedure.

^b Tests were performed using the NASA linear bearing test procedure.

^c Derived from design allowable data for AS4/3501-6 (assumes a 60% fibre volume fraction) [113].

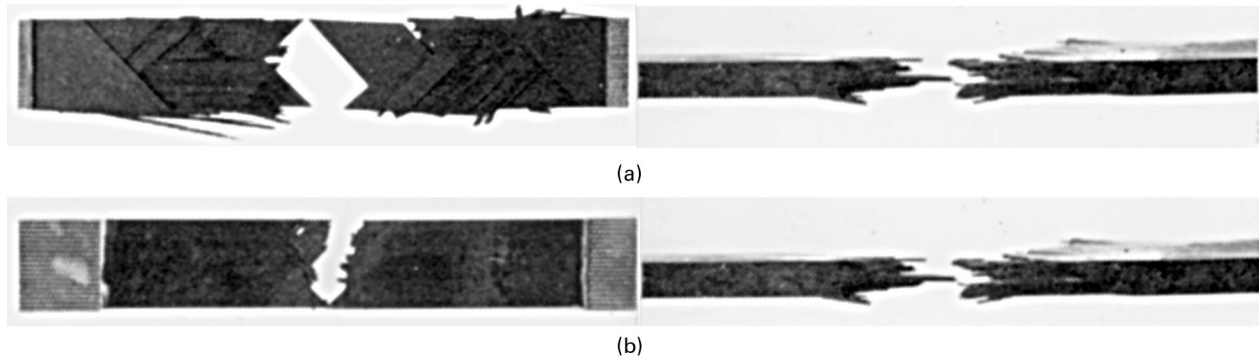


Fig. 20. Typical fractographs of tensile specimens of (a) unidirectional prepreg tape and (b) non-crimp, composites [64].

[63–65,68,69,73], the research currently undertaken is still rather disjointed for a comprehensive understanding of the performance of the material to be established.

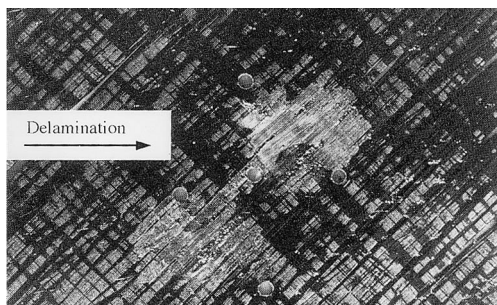
There are significant cost incentives to be gained with non-crimp fabric in comparison with unidirectional prepreg tape composites. These include reduced wastage and labour, adaptability to automation, and virtually unlimited shelf life without the need for refrigeration. Limitations arise from issues such as relatively higher raw material cost, impracticality in terms of ply dropoffs, and restrictions on the number of fabric types available commercially. The overall cost implication is, therefore, an important consideration when deciding between the more traditional unidirectional prepreg tapes and non-crimp composites. Clayton et al. [77], for example, have shown that stringers for an all-composite wing can be cost-effectively produced with non-crimp, than with unidirectional prepreg tape, composites whilst adequately satisfying structural requirements. The work of Bischoff et al. [55] and Franzke et al. [57] also suggest

promise for cost savings in using non-crimp fabric, over random reinforcement, for glass reinforced concrete walls. Niedermeier and Horsting [78] further demonstrated that non-crimp composites can be more cost-effective than more conventional reinforcements, in this case woven fabric, in their trials to build a railway coach.

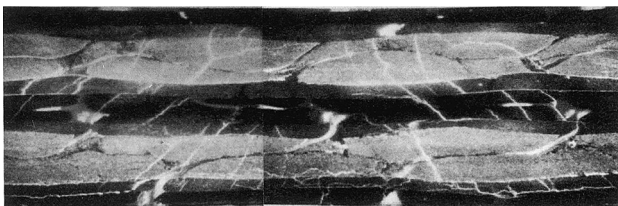
6.4. Sandwich structure preforms

3D knitted preforms having two skin structures integrally connected by pile fibres (Fig. 22) show potential not only for improving both skin–core peel properties as well as cost efficiency (since secondary bonding of skins to core is avoided thereby reducing overall cost of the sandwich structure) of more conventional sandwich structures, they also have the added advantage of better forming properties and energy absorption capabilities.

The production of 3D knitted sandwich preforms is a



(a)



(b)

Fig. 21. (a) Plan (deply), and (b) cross-sectional, views of a typical impact damage zone in non-crimp composites [65].

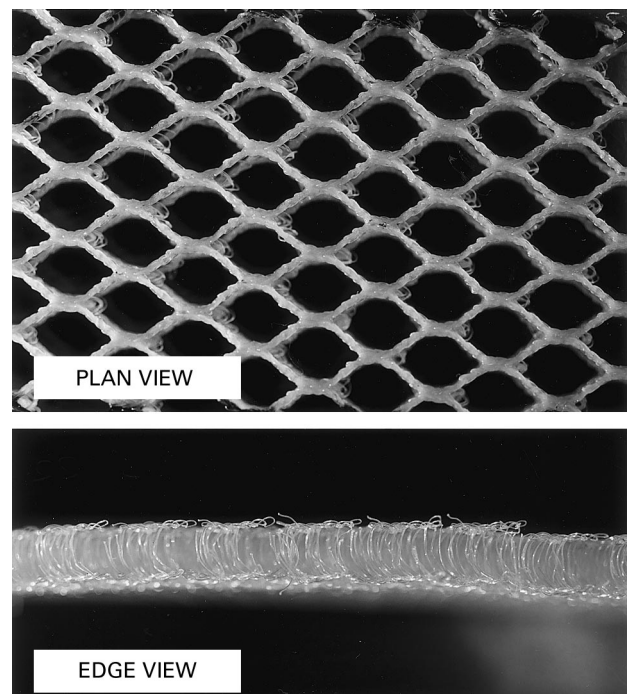


Fig. 22. An example of 3D knitted sandwich (preform) structure [38].

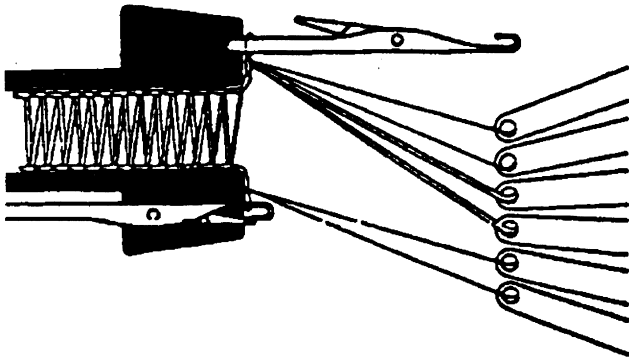


Fig. 23. Schematic diagram of the knitting process for producing 3D sandwich preforms [38].

relatively new innovation [14,15,54,79–81]. These preforms are produced on double needle bar Raschel knitting machines whereby the top and bottom skins are simultaneously knitted (Fig. 23). The two needle bars can be independently programmed so that two different skin structures can be obtained if required. Yarns are supplied by means of two guide bars and during the knitting process the two warp-knit skins are periodically connected to each other by means of the two groups of yarns intermittently swapping between the two needle bars. As a result, the pile fibres become an integral part of the skins thereby imparting superior skin–core peel properties to the sandwich structure. Secondary bonding of skins to core is also avoided thus reducing the overall cost of the sandwich structure [14,15,80]. Although improved skin–core peel strength is obtained with the use of 3D integrally woven sandwich panels [80], 3D knitted sandwich structures are expected to also have better formability [14,15,79] than many traditional sandwich materials. Consolidation of these fabrics is achieved by either—(1) using a relatively high viscosity resin and wet layup with the aid of a roller to promote resin impregnation, or (2) using a relatively low viscosity resin in a continuous bath [14].

Preliminary work carried out by Philips et al. [14,15] on

3D sandwich panels knitted from modified and unmodified mono and multifilaments of polyethyleneterephthalate (PET) revealed that compression, impact and flexural properties are, as expected, highly dependent on the core properties, which in turn are controlled by the cell structure, the degree of resin impregnation and pile fibre density [14]. In addition the density of the composites and the fibre orientation with respect to loading direction (which could be altered by deforming the preform) also influence the flexural strength of these composites [15]. Compared to foam materials, the 3D knitted sandwich structures are comparable in flexural stiffness and compression strength to polymethylacrylimide (PMI) foam, and in impact energy absorption capability, to polystyrene [14].

6.5. Fully fashioned preforms

The fully fashioned knitting technology has been used to produce near-net-shape reinforcement for engineering composites, but as yet only at demonstration levels. Whilst near-net-shape knitting is possible on a flat-bed weft knitting machine by controlling needle selection and motion, and continually changing the knit architecture [2,82], additional needle beds are required for producing 3D (multi-layer) fully fashioned fabrics [82,83]. These needles are needed both to create the different layers of knits as well as to facilitate the transfer of yarns between the layers. Several shaped knitted demonstration components have been highlighted in the literature including more generic shapes such as T-shape connectors, cones, pipes with an integrated flange [2,84], and I-beams [83]. More specific knitted components such as jet engine vanes [82,85], a rudder tip fairing for a mid-size jet engine aircraft [86], and medical prosthesis [87] have also been demonstrated. Despite these successful trials, at least on a technical level, the development of 3D near-net-shape composites is very much in its embryonic stage, and the high cost of machine and software development stands in the way of more rapid progress.

7. Analytical and numerical models

7.1. Elastic properties

The first attempt to theoretically estimate the stiffness of a plain weft-knit composites was carried out by Rudd et al. [5] by using a combination of the rule-of-mixtures and a reinforcement efficiency factor, η . The factor was originally proposed by Krenchel [88] for predicting the elastic modulus of short-fibre-reinforced cement composite. It was used by Rudd et al. [5] to quantify the influence of yarn orientation by means of a fabric loop model which ignores any effect of yarn crossover at interlocking regions of a flat knitted fabric. Stiffness predictions based on the model was on the whole lower than experimentally determined except for the elastic modulus in the wale direction which

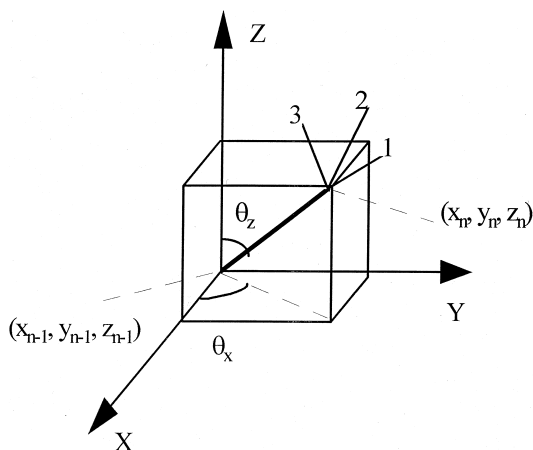


Fig. 24. A yarn segment orientation in the global coordinate system.

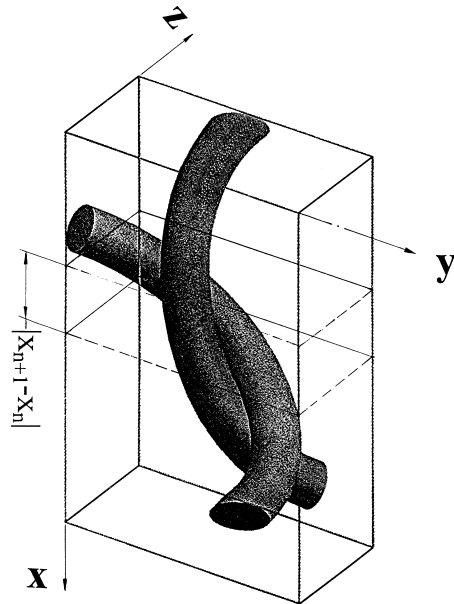


Fig. 25. A typical sub-volume cutting from the RVE of a plain weft knitted fabric composite.

yielded fairly good agreement between the two sets of data. The same model was later used by Mayer [89] and Ramakrishna and Hull [90] for knitted carbon fibre reinforced polyetheretherketone and epoxy matrix composites, respectively. This 1D approach has a limited capability since it is only able to predict normal elastic modulus in the load direction but not other elastic constants such as shear modulus or Poisson's ratio.

Ramakrishna et al. [91], Hamada et al. [92] and Huysmans et al. [93] applied finite element techniques to predict tensile properties of knitted fabric composites. It was found that even by just assuming a representative volume element (RVE), the geometry of a knitted fabric composite can be still quite complicated and consequently the generation of the 3D mesh proved very laborious and hence time-consuming. For simplification, Ramakrishna et al. [91] and Hamada et al. [92], and Huysmans et al. [93], respectively, used beam and volume elements to represent the matrix, whilst they all used beam elements to model the yarn architecture. Good correlations between predicted and measured elastic modulus were obtained although the results for shear modulus was less satisfactory [93].

In a separate study, Ramakrishna [94] applied a pseudo-3D model consisting of laminated shell elements to plain

weft-knit composites. Only the predictions of elastic moduli in the wale and course directions were verified against experimental data, however, the validity of this approach for estimating other elastic constants is yet to be established. Gowayed and colleagues [95–97] developed a finite element model for estimating thermomechanical properties of knitted fabric composites. In this model, both the fibres and matrix were discretised using hexahedral brick elements. Comparisons between predicted and measured data appeared to suggest that the model has some merit. However, results obtained from finite element analyses are sensitive to the boundary conditions imposed on the RVE [98]. The actual boundary conditions are difficult to precisely define since the fibre architecture of knitted composites is highly complex. Therefore, in most cases, it is more practical to use analytical methods than finite element techniques.

Micromechanical models have been successfully used for predicting the mechanical properties of unidirectional fibre and woven fabric reinforced composites. Application of the micromechanical method for estimating elastic properties of knitted composites is a relatively recent approach and hence there is very little published work in the open literature. The few published works all follow a similar two-step analysis procedure. In the first step, a unit cell or RVE is partitioned into a number of infinitesimal elements (sub-cells) which are analysed by means of unidirectional micromechanics formulae in local coordinate systems. A tensor transformation rule is applied to transform the resultant elements from a local coordinate system to a global one (Fig. 24). In the second step, an averaging scheme (of either the Voigt [99] or the Reuss method [100]) is used to obtain the overall stiffness/compliance matrix of the unit cell.

Ruan and Chou [101] applied these concepts to composites reinforced with plain and rib weft-knit fabrics. In the first of the two-step analysis, the yarn segments in a typical sub-cell were considered as unidirectional laminae and a series model [102] was used to predict the stiffness matrices of these unidirectional laminae. The resultant yarn stiffness matrices were transformed to the global coordinate system using coordinate-transformation formulae. The Voigt method was finally used to obtain the overall stiffness matrix of the sub-cell. In the second step, the compliance matrices of all the sub-cells were averaged using the Reuss method to give the overall compliance of the unit cell. Only limited success was achieved [101].

A similar analysis procedure was used by Gommers et al.

Table 6

Elastic properties of knitted glass fibre fabric reinforced epoxy composites [106] (values in square brackets are standard deviations)

Fibre volume fraction (V_f)	Property	E_{xx} (GPa)	E_{yy} (GPa)	E_{zz} (GPa)	G_{xy} (GPa)	G_{xz} (GPa)	G_{yz} (GPa)	ν_{xy}	ν_{xz}	ν_{yz}
0.095	Experimental	5.38 [0.33]	4.37 [0.07]	—	—	—	—	0.48 [0.13]	—	—
	Theoretical	5.61	4.59	4.48	1.91	1.75	1.63	0.369	0.354	0.367
0.323	Experimental	10.28[0.35]	8.49[0.21]	—	—	—	—	—	—	—
	Theoretical	9.47	7.21	7.00	3.13	2.78	2.53	0.371	0.351	0.368

Table 7

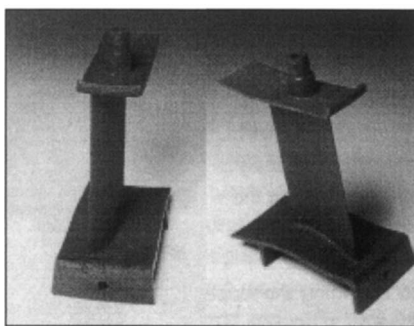
Tensile strength of plain knitted fibre fabric composites [103,108] (Note: Parameters used: $E_f = 74$ GPa, $E_m = 3.6$ GPa, $\nu_f = 0.23$, $\nu_m = 0.35$, $E_T^m = 480$ MPa, $\sigma_Y^m = 20$ MPa, $\sigma_u^f = 1933$ MPa, $\sigma_u^m = 31.5$ MPa, $d = 0.0445$ cm, $D_y = 177.8$, $K = 0.45$, $\rho_f = 2.54$ g/cm³, $C = 2.5$ loop/cm, $W = 2$ loop/cm, $t = 0.06$ cm)

Load axis	Composite strength (MPa)		Maximum normal stress (MPa)		Predicted failure	
	Measured	Model	Fibre	Matrix	Fibre	Matrix
Wale	62.83	65.4	408.5	31.51	No	Yes
Course	35.3	37.56	55.36	31.53	No	Yes

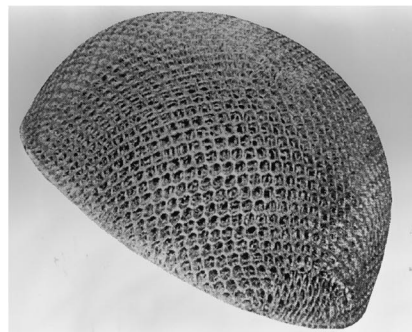
[102] for warp-knit composites, and by Ramakrishna [11,103] for plain weft-knit composites. Gommers et al. [102] defined the compliance matrix of a typical sub-cell according to the Chamis [104] formulae and obtained lower and upper bound results for the properties of the composites using the Voight [99] and Reuss [100] methods, respectively. The difference between the two boundary limits were, however, quite large. The approach adopted by Ramakrishna [11,103] differed slightly in that the Chamis formulae were used to define the compliance matrix

of the yarn segments in the sub-cell. The analytical model of Leaf and Glaskin [105] was adopted for describing the geometry of the plain weft-knit fabrics. This modelling approach allowed the influence of various geometric parameters including lineal density of the yarn, fibre volume fraction and fabric stitch density on the overall elastic properties of the composites to be investigated. Ramakrishna [11,103] arrived at the same conclusions as Ruan and Chou [101].

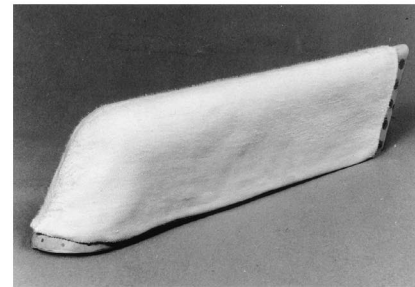
More recently, Huang et al. [106] improved upon the modelling procedure of Ramakrishna [11,103] by proposing



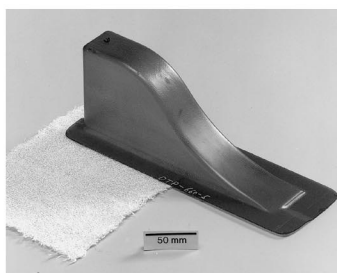
(a)



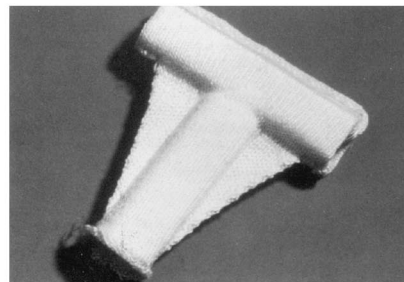
(b)



(c)



(d)



(e)



(f)

Fig. 26. Examples of knitted composites. (a) Silicon carbide knitted ceramic composite guide vanes for a jet engine [82,85]. (b) 3D sandwich knitted preform for a cycling helmet [38]. (c) Net-shape glass knitted preform for a rudder tip fairing of a passenger aircraft [86]. (d) Glass knitted composite for a door component of a helicopter [86]. (e) Fully fashioned glass preform for stiffened T-joints [84]. (f) An indirect (left) and a direct (right) socket for leg prostheses made from glass and Kevlar knitted composites, respectively [110].

a new micromechanical model, called the bridging matrix model, for estimating the elastic constants of unidirectional composite lamina. They [106] used the model by Leaf and Glaskin [105] to describe the fabric geometry whereby the yarns in a representative volume (Fig. 25) were divided into a series of straight segments to which the bridging stiffness matrix was applied. The compliance or stiffness matrix was described in local coordinates where only one yarn segment in the representative volume was considered. To obtain the overall mechanical properties of the composite in a representative volume, the matrix is first transformed into the global coordinates based on the tensor transformation principle and then the contributions of all the segments of yarns are combined using the compliance averaging method or the Reuss method.

Table 6 gives some indication of the ability and effectiveness of the bridging matrix approach for stiffness prediction. It is noteworthy that the most important feature of this new bridging matrix model is that it can be easily extended to estimate the inelastic and strength properties of the composites.

7.2. Strength properties

The prediction of strength of textile composites is significantly more challenging than determining their elastic modulus. Judging from the limited number of published works, particularly for knitted composites, it is fair to say that this area has been largely neglected. Ramakrishna and Hull [90] and Ramakrishna [103] achieved limited success with predicting the tensile strength of knitted fabric composites by estimating the breaking load of fibre yarn bundles that bridge the fracture plane. Mayer and Wintermantel [107] extended the approach which unfortunately also yielded poor correlation between predicted and experimental data. Equally poor predictions were obtained from finite element models [92] where tensile strength was grossly overestimated.

The micromechanical approach advanced by Huang et al. [106] (described in Section 7.1) was extended [108] with considerable success for tensile strength prediction of knitted fabric composites. The strength model essentially assumes that the elasto-plastic behaviours of the constituent fibre and matrix can be independently expressed based on the Prandtl–Reuss plastic flow theory [109], which can then be combined using the bridging matrix. It should be noted that the non-diagonal elements of the bridging matrix in the plastic region may be different from those in elastic regime. This approach can be applied to an RVE of a knitted composite in conjunction with an appropriate failure criterion for estimating strength where the tensile strength of the composite is assumed to coincide with the ultimate stress of either the fibre or matrix, whichever is lower.

Using unidirectional laminates, Huang et al. [108] derived properties for a fibre and a matrix that were used by Ramakrishna [103] for an earlier work. This earlier work

enabled Huang and his colleagues [108] to compare strength predictions with an equivalent set of experimental results [103], as summarised in Table 7. The results outlined in the table are encouraging and suggest that this semi-empirical model warrants further development. It will be noted that so long as the ultimate strengths of the fibre and matrix can be determined, respectively, from the overall limit stresses of the unidirectional lamina in the longitudinal and transverse directions, the particular values of the yield parameters of the matrix (yield stress and hardening modulus) do not have any significant influence on the predicted composite strength values. This is because the ultimate stress of the composite is mainly dependent on the tensile strengths of the constituent materials, and not parameters relating to material yield, although the latter does affect the predicted composite ultimate strain values.

8. Conclusions and implications

The advent of knitted reinforcements has presented the composites community with some novel options in materials selection. 2D and 3D flat fabrics, and fully fashioned preforms have been trialled with considerable success for niche engineering applications, although most of the applications are still at the concept level.

Although knitted composites are inferior to many of their more traditional counterparts with respect to in-plane strength and stiffness, they are generally superior in terms of energy absorption, bearing and notched strengths, and fracture toughness. In addition, knitted fabrics also have low resistance to deformation, and hence exceptional formability. There is, as yet, no fatigue data available for these materials and hence the performance of knitted composites under fluctuating stresses/strains is not known. Varying knit architecture and knit parameters such as loop length and stitch density can influence mechanical properties of the composite. Notwithstanding this, in-plane mechanical properties can also undergo profound changes upon distortion to the fabric. This presents some degree of freedom to composite engineers for manipulating both the properties as well as the isotropy of the knitted composite to suit a particular application. Knitted composites are also cost-effective since most conventional knitting machines can be used with little or no modification to produce advanced fibre knitted fabrics. Whilst knitting-induced fibre damage is almost inevitable, the overall composite performance is hardly affected by it due to bridging stress transfer over the damaged region. With these characteristics, the future of knitted composites is believed to lie in complex shaped impact resistant, low to medium loaded components, where a right balance of the degree of formability and the prerequisite in-plane properties can be achieved. A wide range of technology demonstrators have been produced including various fairings for aerospace applications [86], medical prostheses [87,110], and a cycling helmet for competitive

sports [38]. The fully fashioned technology has also been demonstrated, among them, fairings, produced from glass [86], for aerospace applications, and a Rolls-Royce exhaust guide vane, which is a static engine part, manufactured from silicon carbide and consolidated via the chemical vapour deposition (CVD) technique, for the aeroengine industry [82,85]. Fig. 26 shows some of these components.

Introducing floats stitches and inserting differing amounts of virtually straight in-lay yarns into basic knit structures have achieved varying degrees of success in improving the in-plane properties of knitted composites. Amongst the most popular of these variants is the 3D non-crimp composites whereby multiaxial, multilayer reinforcement are produced in one-step fabric manufacturing processes, which unfortunately makes the raw material cost higher. Non-crimp composites are nevertheless strong contenders for structural applications since the in-lay fibres can result in very similar properties to the more conventional unidirectional prepreg tape composites. Apart from that, non-crimp fabrics come with several other advantages such as better formability, reduced scrap and labour, adaptability to automation, and virtually unlimited shelf life without the need for refrigeration. They also have impact performance which at least matches that of unidirectional prepreg tape. Consequently, careful overall cost versus application analysis needs to be carried out before discarding the material purely based on the relatively higher fabric cost. Like their 2D knitted composite cousins, 3D warp-knit, non-crimp composites have captured a lot of interest from the engineering community. In particular, they appear to be most popular with the transport (e.g. wing stringers [77], crash elements [59,61], motorcycle rims and bus roofs [81], railway coaches [78]) and construction/civil industries (e.g. concrete walls [55,57]).

Finally, whilst the acceptance of knitted composites by the engineering community depends very much upon the availability of a reliable database for mechanical properties and a good understanding of the fracture and failure mechanisms of these materials, a proven capability for predicting such properties is also vital. Analytical models based on micromechanical approaches have been applied with partial success for estimating the elastic constants of knitted fabric composites. Further investigations are needed to improve correlation between theoretical predictions and experimental measurements. Compared with finite element methods, analytical methods are superior and they give closed-form expressions for the required mechanical properties. The dependency of these properties on the microstructural parameters of knitted fabrics can be studied with much less effort. The relationships between the properties of constituent materials and the fabric structure on the overall strength properties of the composite is yet to be fully identified. Further, there appears to be a lack of attempts to analyse damage evolution and inelastic behaviours of knitted composites, both of which warrant further investigation. Solutions to all these issues are crucial

for opening up the path towards less laborious and more accurate ways of predicting the properties of knitted composites, and hence capturing greater confidence and wider acceptance for the material.

References

- [1] Hearle JWS. Textile for composites—Part I: The general scene. *Textile Horizons* 1994;14(6):12.
- [2] Epstein M, Nurmi S. Near net shape knitting of fibre glass and carbon for composites. (Proc. Conf.) 36th International SAMPE Symposium. 15–18 April 1991. p. 102.
- [3] Höhfeld J, Drew MJ, Kaldenhoff R. Consolidation of thick, close, circular, knitted glass fibre textiles with epoxy resin into flat panels, tubes and T-profiles. (Proc. Conf.) International Conference on Flow Processes in Composite Materials, Ireland, 7–9 July 1994. p. 120–42.
- [4] Taylor E. Bring in the reinforcements. *Adv Comp Engng* 1990;January:17.
- [5] Rudd CD, Owen MJ, Middleton V. Mechanical properties of weft knit glass fibre/polyester laminates. *Comp Sci Tech* 1990;39:261.
- [6] Chou S, Chen H-C, Lai C-C. The fatigue properties of weft-knit fabric reinforced epoxy resin composites. *Comp Sci Tech* 1992;45:283.
- [7] Leong KH, Falzon PJ, Bannister MK, Herszberg I. An investigation of the mechanical performance of Milano-rib weft knitted glass/epoxy composites. *Comp Sci Tech* 1998;58(2):239.
- [8] Herszberg I, Falzon PJ, Leong KH, Bannister MK. Bearing strength of glass/epoxy composites manufactured from weft-knitted E-glass fabric. (Proc. Conf.) 1st Australasian Congress on Applied Mechanics, Melbourne, Australia, 21–23 February 1996. The Institution of Engineers, Australia, 1996;1:279–84.
- [9] Gohl EPG, Vilensky LD. Knitting, textile for modern living, 4. Cheshire: Longman, 1991 chap 31, p. 213–45.
- [10] Australian Standard Methods of Test for Textiles. Determination of the number of wales and courses per unit length in knitted fabric, AS 2001.2.6. 1981.
- [11] Ramakrishna S. Characterization and modelling of tensile properties of plain weft knit fabric-reinforced composites. *Comp Sci Tech* 1997;57:1.
- [12] Andersson C-H, Eng K. Weft insert co-knitting and lost yarn preforming, new fabric based techniques for composite materials preforming. Presented at Forum on New Materials, Florence, Reprint. 1994.
- [13] Lau KW, Dias T. Knittability of high-modulus yarns. *J Textile Inst* 1994;85(2):173.
- [14] Phillips D, Verpoest I, van Raemdonck J. 3D-knitted fabrics for sandwich panels. (Proc. Conf.) Texcomp-3. 1996. 18/1.
- [15] Phillips D, Verpoest I, van Raemdonck J. Optimising the mechanical properties of 3D-knitted sandwich structures. (Proc. Conf.) 11th International Conference on Composite Materials, Gold Coast, Australia, 14–18 July 1997;5:211–18.
- [16] Ramakrishna S, Hull D. Energy absorption capability of epoxy composite tubes with knitted carbon fibre fabric reinforcement. *Comp Sci Tech* 1993;49:349.
- [17] de Haan J, Kameo K, Nakai A, Fujita A, Mayer J, Wintermantel E, Hamada H. Notched strength of knitted fabric composites, (Proc. Conf.) 11th International Conference on Composite Materials, Gold Coast, Australia, 14–18 July 1997;5:219–26.
- [18] Andersson C-H, Christensson B, Wickberg A, Pisanikovski T. Handleability of fibres, machinability of composites and the working environment. (Proc. Conf.) Seventh European Conference on Composite Materials. The Institute of Materials 1996;2:415–20.
- [19] Andersson C-H, Christensson B, Wickberg A, Nilsson A, Larsson

- L-G. Handleability, dust and damage of reinforcement fibres. (Proc. Conf.) Texcomp-3. 1996; 21/1.
- [20] Chou S, Wu C-J. A study of the physical properties of epoxy resin composites reinforced with knitted glass fibre fabrics. *J Rein Plas Comp* 1992;11:1239.
- [21] Nguyen M, Leong KH, Herszberg I. The effects of deforming knitted glass preforms on the composite compression properties. (Proc. Conf.) 5th Japan International SAMPE Symposium and Exhibition, Tokyo, Japan. 28–31 October 1997. p. 653–58.
- [22] Wu WL, Kotaki M, Fujita A, Hamada H, Inoda M, Maekawa Z. Mechanical properties of warp-knitted fabric-reinforced composites. *J Rein Plas Comp* 1993;12:1096.
- [23] Anwar KO, Callus PJ, Leong KH, Curiskis JJ, Herszberg I. The effect of knit architecture on the mechanical properties of knitted composites, (Proc. Conf.) 11th International Conference on Composite Materials, Gold Coast, Australia, 14–18 July 1997;5:328–37.
- [24] Ramakrishna S, Hull D. Tensile behaviour of knitted carbon-fibre-fabric/epoxy laminates—Part I: experimental. *Comp Sci Tech* 1994;50:237.
- [25] Mayer J, Ha, S-W, de Haan J, Ruffieux K, Koch B, Wintermantel E. Knitted carbon fibres: new low cost, high performance fibre structures for reinforced plastics. (Proc. Conf.) Internationales Techtextil-Symposium, 3.2, Lecture 329. 1993; 1.
- [26] Leong KH, Nguyen M, Herszberg I. The effects of deforming knitted preforms on the tensile properties of resultant composite laminates. (Proc. Conf.) 11th International Conference on Composite Materials, Gold Coast, Australia, 14–18 July 1997;5:201–10.
- [27] Verpoest I, Dendauw J. Mechanical properties of knitted glass fibre/epoxy resin laminates. In: Bunsell AR, Jamet JF, Massiah A, editor. (Proc. Conf.) ECCM-5. April 7–10, 1992, Bordeaux, France, p. 927–32.
- [28] Verpoest I, Dendauw J. Mechanical properties of knitted glass fibre/epoxy resin laminates. (Proc. Conf.) 37th International SAMPE Symposium. 9–12 March 1992. p. 369.
- [29] Verpoest I, Gommers B, Huymans G, Ivens I, Luo Y, Pandita S, Phillips D. The potential of knitted fabrics as a reinforcement for composites, (Proc. Conf.) 11th International Conference on Composite Materials, Gold Coast, Australia, 14–18 July 1997;1:108–33.
- [30] Wu WL, Hamada H, Kotaki M, Maekawa Z. Design of knitted fabric reinforced composites. *J Rein Plas Comp* 1995;14:1032.
- [31] Leong KH, Nguyen M, Herszberg I. The effects of deforming knitted glass preforms on the basic composite mechanical properties. *J Mater Sci* 1999;34(10):2377.
- [32] Leong KH, Khondker OA, Herszberg I. Variation in composite tensile properties due to biaxial deformation of knitted glass fabrics. (CD-ROM Proc. Conf.) 12th International Conference on Composite Materials, Paris, France, 5–9 July 1999, Paper 728.
- [33] Khondker OA, Leong KH, Herszberg I. An investigation of the structure–property relationship on knitted composites. Submitted for publication.
- [34] Karger-Kocsis J, Czígány T, Mayer J. Fracture behaviour and damage growth in knitted carbon fibre fabric reinforced polyethylmethacrylate. Plastic, Rubber and Composite Processing and Applications 1996;25(3):109.
- [35] Ramakrishna S, Hamada H, Rydin RW, Chou TW. Impact damage resistance of knitted glass fibre fabric reinforced polypropylene composites. *Sci Engng Comp Mater* 1995;4(2):61.
- [36] Ruan X, Chou T-W. Failure behavior of knitted fabric composites. *J Rein Plas Comp* 1998;32(3):198.
- [37] Rios CR, Ogini SL, Lekakou C, Leong KH. The relationship between fibre architecture and cracking damage in a knitted fabric reinforced composite. (CD-ROM Proc. Conf.) 12th International Conference on Composite Materials, Paris, France, 5–9 July 1999, Paper 1035.
- [38] Verpoest I. Advanced three-dimensional textile sandwich composites. Course Notes. CRC-ACS, 29 and 31 January 1997, Melbourne and Sydney, Australia.
- [39] Mouritz AP, Baini C, Herszberg I. Mode I interlaminar fracture toughness properties of advanced textile fibreglass composites. *Composites Part A* 1999;30(7):859.
- [40] Reber R, de Haan J, Petitmermet M, Mayer J, Wintermantel E. Failure behavior of weft-knitted carbon fibre reinforced PEEK. (Proc. Conf.) First Asia–Australasian Conference on Composite Materials, Osaka, Japan. 1998, vol. 1. 407–14.
- [41] Ramakrishna S, Hull D. Energy absorption in knitted fabric reinforced polymer matrix composites. In: Dattaguru, editor. (Proc. Conf.) Advances in structural testing, analysis and design, New Delhi, India: Tata McGraw-Hill, 1990. pp. 69–74.
- [42] Arendts FJ, Schaich T, Drechsler K. Energy absorption and penetration resistance of various new composite materials. (Proc. Conf.) 13th International European Chapter Conference of SAMPE, Hamburg, Germany. 11–13 May 1992.
- [43] Hull D, Shi YB. Damage mechanism characterisation in composite damage tolerance investigations. *Comp Struct* 1993;23(2):99.
- [44] Sarlin J, Pentti P, Järvelä. A new type of knitted reinforcing fabrics and its application (Proc. Conf.) Fourth European Conference Composite Materials. 1990. p. 621–23.
- [45] Ko FK, Krauland K, Scardino F. Weft insertion warp knit for hybrid composites. In: Hayashi T, Kawata K, Umekawa S, editors. Proceedings of ICCM-IV. Tokyo, Japan. 1982. p. 1169–76.
- [46] Ramakrishna S, Hull D. Mechanical properties of knitted fabric composites. (Proc. Conf.) Eighth International Conference on Composite Materials, Hawaii, USA. 1991;6:A1–A10.
- [47] Anon. Biaxial reinforced multilayer weft knitting. (Proc. Conf.) Texcomp-3. Aachen, Germany. 1996. 2pp.
- [48] Offermann P. Biaxial reinforced knitted fabrics for composite reinforcement. Promotional Leaflet, T.U. Dresden, Germany. 1997.
- [49] Stumpf H, Mäder E, Baeten S, Pisanikovski T, Zäh W, Eng K, Anderson C-H, Verpoest I, Schulte K. New thermoplastic composite preforms based on split-film warp-knitting. (Proc. Conf.) Texcomp-3. 1996. 20/1.
- [50] Stumpf H, Mader E, Baeten S, Pisanikovski T, Zah W, Eng K, Andersson CH, Verpoest I, Schulte K. New thermoplastic composite preforms based on split-film warp-knitting. *Composites Part A* 1998;29(12):1511.
- [51] Baeten S, Verpoest I, Stumpf H, Schulte K, Zäh W, Mäder E, Pisanikovski T, Andersson C-H, Eng K. New low cost textile preforms and short cycle processing techniques for thermoplastic composites, (Proc. Conf.) 11th International Conference on Composite Materials, Gold Coast, Australia, 14–18 July 1997;5:227–37.
- [52] Andersson C-H, Eng K.. Split film based weft insert warp co-knitting and lost yarn preforming, two new routes for composite materials preforming. Proceedings of the ECCM-6. 1993. p. 237–42.
- [53] Wagener G. Stitch-bonded non-crimp products—new possibilities for the reinforcement of composites. (Proc. Conf.) Internationales Techtextil-Symposium, 3.2, Lecture 325, 1993. p. 1.
- [54] Anand S. Warp knitted structures in composites. (Proc. Conf.) Seventh European Conference in Composite Materials. London, UK, 14–16 May 1996;2:407–13.
- [55] Bischoff Th, Wulforth B, Franzke G, Offermann P, Bartl A-M, Fuchs H, Hempel R, Curbach M, Pachow U, Weiser W. Textile reinforced concrete facade elements—an investigation to optimize concrete composite technologies. (Proc. Conf.) 43rd Int. SAMPE Symp., Anaheim, CA, USA, May 31–June 4, 1998;43:1790.
- [56] Kress G. Understanding reinforcement concepts (Part II). *Comp. Fabrication* 1998;April:12.
- [57] Franzke G, Offermann P, Bischoff T, Wulforth B. Multi-axial warp knitted layers—a textile for reinforcing concrete. (Proc. Conf.) 11th International Conference on Composite Materials Gold Coast, Australia, 14–18 July 1997;2:870–80.
- [58] Liba Pamphlet.
- [59] Hörsting K, Wulforth B, Kaldenhoff R, Offermann P, Franzke G, Diestel O, Engelmann U. Properties of components made of reinforcing layers. (Proc. Conf.) Internationales Techtextil-Symposium, 3.1, Lecture 318, 1993. p. 1.

- [60] Dexter HB, Hasko GH. Mechanical properties and damage tolerance of multiaxial warp-knit composites. *Comp Sci Tech* 1996;56(3):367.
- [61] Hörsting K, Wulforth B, Franzke G, Offermann P. New types of textile fabrics for fibre composites. *SAMPE J* 1993;29(1):7.
- [62] O'Meara R. Private Communication, ROM Development Corporation, Newport, RI, USA. 1997.
- [63] Hogg PJ, Ahmadnia A, Guild FJ. The mechanical properties of non-crimped fabric-based composites. *Composites* 1993;24(5):423.
- [64] Bibo GA, Hogg PJ, Kemp M. Mechanical characterisation of glass- and carbon-fibre-reinforced composites made with non-crimp fabrics. *Comp Sci Tech* 1997;57(9–10):1221.
- [65] Bibo GA, Hogg PJ, Backhouse R, Mills A. Carbon-fibre non-crimp fabric laminates for cost-effective damage-tolerant structures. *Comp Sci Tech* 1998;58(1):129.
- [66] Mouritz AP, Leong KH, Herszberg I. A review of the effect of stitching on the in-plane mechanical properties of FRP composites. *Composites Part A* 1997;28A(12):979.
- [67] DeWalt PL, Reichard RP. Just how good are knitted fabrics? *J Rein Plas Comp* 1994;13:908.
- [68] Hamada H, Sugimoto K. Joint strength of knitted composites, (Proc. Conf.) *Texcomp-4*, Osaka, Japan. 12–14 October 1998. P-23-1–8.
- [69] Wang Y, Li J, Do PB. Properties of composites laminates reinforced with E-glass multiaxial non-crimp fabrics. *J Comp Mat* 1995;29(17):2317.
- [70] Bibo GA, Hogg PJ, Kemp M. Mode II interlaminar toughness of glass and carbon fibre reinforced non-crimp fabric and unidirectional prepreg tape laminates. Submitted for publication.
- [71] Backhouse R, Blakeman C, Irving PE. Mechanisms of toughness enhancement in carbon fibre non-crimp fabrics. (Proc. Conf.) Third International Conference on Deformation and Fracture of Composites, Surrey, UK, 27–29 March 1995. p. 307–16.
- [72] Turmel DJ-P, Szpicak J-A, Singh S, Partridge IK. Crack initiators and pre-cracking techniques for fracture testing of polymer-matrix composites. (Proc. Conf.) Third International Conference on Deformation and Fracture of Composites, Surrey, UK, 27–29 March 1995. p. 190–9.
- [73] Kay ML, Hogg PJ. Damage tolerance of non-crimped fabric composites. In: Bunsell AR, Kelly A, Massiah A, editors. (Proc. Conf.) Sixth European Conference on Composite Materials. The Institute of Materials, 20–24 September 1993, Bordeaux, France, 1993. p. 361–9.
- [74] Du G-W, Ko F. Analysis of multiaxial warp-knit preforms for composite reinforcement. *Comp Sci Tech* 1996;56(3):253.
- [75] Karbhari VM. Impact characterisation of RTM composites—1: metrics. *J Mater Sci* 1997;32:4159.
- [76] Mäder E, Skop-Cardarella K, Wegner A, Zäh W. Processing technique and binding yarn influences on the performance of composite materials. (Proc. Conf.) *Texcomp-4*, Osaka, Japan, 12–14 October 1998. O-26-1–8.
- [77] Clayton G, Falzon PJ, Georgiadis S, Liu XL. Towards a composite civil aircraft wing. (Proc. Conf.) 11th International Conference on Composite Materials, Gold Coast, Australia, 14–18 July 1997;1:310–9.
- [78] Niedermeier M, Hörsting K. Innovative composite design rail vehicles with multiaxial layer reinforcement fabrics. (Proc. Conf.) *Texcomp-3*, 1996, 22/1.
- [79] Editor. Knitted fabrics have better drape in sandwich structures. *Advanced Composites Bulletin* October 1995. p. 2.
- [80] Verpoest I, Ivens I, van Vuure AW, Gommers B, Vendeuren P, Efstratiou V, Philips D. New developments in advanced textiles for composites. (Proc. Conf.) Fourth Japan International SAMPE Symposium, 25–28 September 1995. p. 644.
- [81] Davies S. Textile for composites. *Tech Textile Int* 1997;December 1996/January 1997:22–4.
- [82] Gibbon J, editor. Knitting in the third dimension. *Textile Horizons* 1994;14(6):22.
- [83] Sheffer E, Dias T. Knitting novel 3-D solid structures with multiple needle bars. (Proc. Conf.) UMIST Textile Conferences—Textile Engineered for Performance, Manchester, UK. Section 3—Textiles for Composites, 20–22 April 1998.
- [84] Rudd CD, Long AC, Kendall KN, Mangin CGE. Liquid moulding technologies, Cambridge, UK: Woodhead Publishing Ltd, 1997. Fig. 6.9, p. 170.
- [85] King JE, Greaves RP, Low H. Composite materials in aeroengine gas turbines: Performance potential vs commercial constraint? Keynote Lecture, Presented at the Sixth European Conference Composite Materials, London, UK, 14–16 May 1996.
- [86] Bannister MK, Herszberg I. The manufacture and analysis of composite structures from knitted preforms. (Proc. Conf.) Fourth International Conference on Automated Composites, 6–7 September 1995, Nottingham, UK. 1995;2:397–404.
- [87] Ramakrishna S, Ramaswamy S, Teoh SH, Hastings GW, Tan CT. Application of textile and textile composite concepts for biomaterials development. (Proc. Conf.) *Texcomp-3*, 1996;27/1.
- [88] Krenchel H. Fibre reinforcement, Copenhagen: Akademisk Forlag, 1964.
- [89] Mayer J. Gestricke aus Kohlenstoffasern für biokompatible Verbundwerkstoffe, dargestellt an einer homoelastischen Osteosynthesplatte, PhD thesis, ETH Zurich, 1994.
- [90] Ramakrishna S, Hull D. Tensile behaviour of knitted carbon-fibre-fabric/epoxy laminates—part II: prediction of tensile properties. *Comp Sci Tech* 1994;50:249.
- [91] Ramakrishna S, Fujita A, Cuong N.K., Hamada H., (1995a). Tensile failure mechanisms of knitted glass fibre fabric reinforced epoxy composites. (Proc. Conf.) Fourth Japan International SAMPE Symposium, 25–28 September 1995. p. 661–6.
- [92] Hamada H, Fujita A, Yokoyama A, Maekawa Z. Unified approach for predicting mechanical behaviors of textile composites. (Proc. Conf.) ACS Meeting, Delaware (USA), 1994. p. 377–85.
- [93] Huysmans G, Gommers B, Verpoest I. A binary finite element model for the effective stiffness prediction of 2D warp knitted fabric composites. (Proc. Conf.) Fourth Int. Conf. on Deformation and Fracture of Comp., Manchester, UK. 1997. p. 309–18.
- [94] Ramakrishna S. Analysis and finite element modelling of elastic behaviour of plain-knitted fabric reinforced composites. *Key Engng Mat* 1997;137:71.
- [95] Gowayed YA. An integrated approach to the mechanical and geometrical modeling of textile structural composites. Doctorate thesis, North Carolina State University, Raleigh, USA. 1992.
- [96] Gowayed YA, Hwang J, Chapman D. Thermal conductivity of textile composites with arbitrary perform structures. *ASTM J Comp Tech Res* 1995;17(1):56.
- [97] Gowayed YA. The effect of voids on the elastic properties of textile reinforced composites. *ASTM J Comp Tech Res* 1997;19(3):168.
- [98] Sun CT, Vaidya RS. Prediction of composite properties from a representative volume element. *Comp Sci Tech* 1996;56:171–9.
- [99] Voigt W. *Wied Ann* 1889;38:573.
- [100] Reuss A. *Z Angew Math Mech* 1929;9:49.
- [101] Ruan X, Chou T-W. Experimental and theoretical studies of the behavior of knitted-fabric composites. *Comp Sci Tech* 1996;56:1391.
- [102] Gommers B, Verpoest I, Van Houtte P. Modelling the elastic properties of knitted-fabric-reinforced composites. *Comp Sci Tech* 1996;56(3):685.
- [103] Ramakrishna S. Analysis and modelling of plain knitted fabric reinforced composites. *J Comp Mater* 1997;31(1):52.
- [104] Chamis CC. Mechanics of composite materials: past, present, and future. *J Comp Technol Res* 1989;11:3–14.
- [105] Leaf GAV, Glaskin A. The geometry of a plain knitted loop. *J Textile Inst* 1955;45:T587–T605.
- [106] Huang ZM, Ramakrishna S, Tay AAO, Teoh SH, Chew CL. A new modeling procedure for estimating the elastic moduli of knitted fabric composites. (Proc. Conf.) Fifth Japan International SAMPE Symposium, Oct. 28–31, Tokyo, 1997. p. 719–24.

- [107] Mayer J, Wintermantel E. Failure behavior of knitted carbon fibre reinforced thermoplastics, Presented at Euromat '95, Venice/Padua, Italy. 1995.
- [108] Huang ZM, Ramakrishna S, Tay AAO. A micromechanical approach to the tensile strength of a knitted fabric composite. *J Comp Mater* 1999; in press.
- [109] Adams DF. Elastoplastic behavior of composites. In: Sendekyj GP, editor. *Mechanics of composite materials*, New York: Academic Press, 1974. p. 169–208.
- [110] Huang ZM, Ramakrishna S. Development of a knitted fabric composite for direct socket application. Submitted for publication.
- [111] Eckold, G., (1994). *Design and manufacture of composite Structures*, Woodhead Publishing Ltd., Cambridge, UK. ISBN 1 85573 051 0, Chapter 2, Table 2.8, p. 34.
- [112] Hull D. A unified approach to progressive crushing of fibre-reinforced composite tubes. *Comp Sci Tech* 1991;40:377.
- [113] Georgiadis S. Private Communication, ASTA Components, Melbourne, Australia, 1998.