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Knitted Preforms for Composite Applications

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ABSTRACT: Knitted structures occupy a special position in composite preforming due to their inimitable characteristics. An insight into the knitted structures with respect to their composite preforming characteristics is presented in this article. Directionality of knitted structures and requirements of high performance fibers for knitting have been discussed. Contourability, net-shape preforming, high dynamic mechanical properties along with easy and rapid manufacturability are the important features of knitted structures to match the composite preform requirements. In this article, the work done in the above areas of research have been critically reviewed.

KEY WORDS: knitting, structural modifications, directional preforms, mechanical properties.

INTRODUCTION

THE SYNERGETIC EFFECT on the properties of the fiber reinforced composite material is much greater than the sum of the individual component properties, wherein compressive strength and stiffness are

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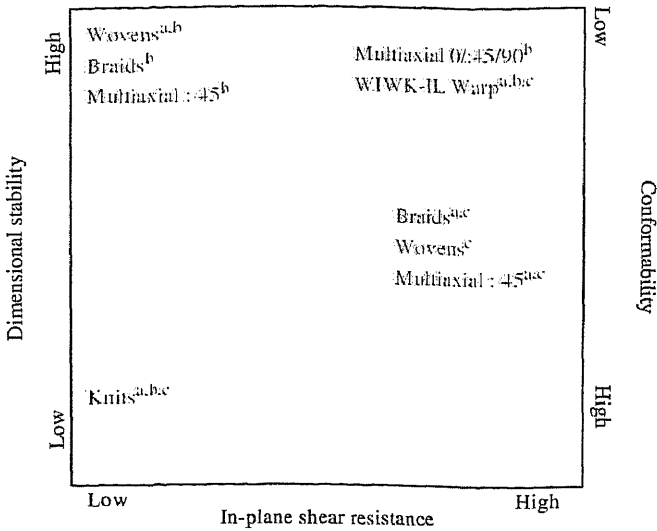
FIGURE 1. Behavior of various fabric structural forms under uniaxial stress [6]: [a]machine (0°) direction; [b]cross (90°) direction; and [c]bias (±45°) direction.

contributed by the reinforcing matrix, and tensile strength is a product of the fiber–matrix synergy [1]. Textile preforms, the assimilated unrigidized fibrous structure, have long been known as prime reinforcement for composite applications, since they are easier to handle, can be made to fit the shapes, and provide versatile design potential due to their structural complexity [2,3]. Though knitted structures have been attempted, lower mechanical properties [4,5] and unexploited technological versatility have rendered their utilization to research level and lower commercial applications in composites. Conformability characteristics, shear resistance, and dimensional stability of various textile preforms with respect to composite applications have been presented in Figure 1 [6]. Although knitted preforms show lower mechanical properties and low dimensional stability compared to that of wovens, high conformability and improved characteristics of modified and multiaxial knits against other textile preforms offer design versatility for composite structural applications.

CLASSIFICATION OF KNITTED STRUCTURES

Knitted structures are developed by knitting, a process of forming fabric by the intermeshing of loops of yarns and on the basis of the loop formation technique, knitted structures are categorized into weft and warp

knits. Sequential feeding of yarn and formation of a loop on each knitting needle effect weft knitting, so that the knitted loops are joined in the horizontal course-wise direction. Warp knitting produces a knitted structure with a simultaneous feeding of yarn and loop formation on each needle in the needle bar during the same knitting cycle, here the yarn path traces along vertical wale-wise direction.

Weft knitted structures are the most commonly designed preforms for composite applications for their ease and manufacturability [7]. Plain knits are produced by the needles knitting as one set, drawing the loops away from the technical back towards the technical face side of the fabric. Reports on structure – property relationship of plain knit reinforced composites [8] and their impact behavior [9] have given an insight into the behavior of knitted fabric reinforced composite materials. Rib structures are the most common preforms for composite application among weft knits [10] and they require two set of needles operating in-between each other so that wales of the face loops stitches with wales of back loops on each side of fabric [11]. Studies on 1 × 1 rib knitted preform after stretch with respect to composite material tensile, bending, and impact performance have provided results indicating improvement in mechanical properties after stretched preforming [12]. Interlock structure is derived from rib structure but requires a separate arrangement of needle knitting back to back in an alternating sequence of two sets so that the two courses of loops show wales of face loop on each side of fabric. Interlock structures have been tried for composite preforming due to its true nature of double layer fabric with strong interlaminar bonding and structural stability [13]. Polyester interlock knit structures have been analyzed for stress–strain behavior and the properties of the composite have been predicted [14]. Resin transfer molded composites using glass Milano rib knits and epoxy resin have been characterized for static and dynamic mechanical properties [15].

Warp knitting is by far the most versatile fabric production system in textiles providing design variations to produce elastic or stable, open or closed structure, flat, tubular or three-dimensional (3-D) structure with a maximum width of over 6 m [16]. Based on the physical and mechanical properties, two guide bar warp knitted structures were categorized into four groups by cluster analysis so that the structure–property correlation can be successfully adopted for designing warp knit preforms to meet desired qualifications [17]. In warp knitted preforms, each increase in the extent of underlap tends to make the structure stronger widthwise whereas pillar or chain stitches are incorporated in the structure to improve the lengthwise strength of the knitted preform [16].

Weft knitting machines have been categorized into circular and flatbed knitting machines based on the type of knitting needlebed employed.

Shaping and structural modifications, generally required for weft knitted fabrics to suit technical applications, such as inlaying, are easily achieved using flatbed knitting machines with additional attachments [11,18,19]. Warp knitting machines are classified into Tricot (single/double guidebars) and Raschel (multiple guidebar) knitting machines. Warp knits for technical applications are either developed on Raschel machines or on modified Tricot machines [11,16,18]. Complete details on developments in the knitting machineries are explained elsewhere [7,11,16,18,19] since these data are voluminous and have been covered in earlier review work [10].

KNITTED FABRIC GEOMETRY AND MODELING

Defining 'Loop' as the unit structural component of plain weft knitted structure, consisting of parts of circles joined by straight lines, Pierce [20] deduced that loop length or stitch length was always 16 times the yarn diameter used for knitting by assuming that loops lay on a cylinder in view of the 3-D properties.

Leaf and Gaskin [22] improvised the single loop shape in relaxed plain knit structure and proposed that the loop structure was constituted by sets of arcs but the actual cover values with respect to nominal cover factor was unpredictable. Based on the assumptions that loops consisted of two elastics joined as mirror images and lay on a surface whose cross section forms a sine function, Leaf provided the best geometrical model for the loop but mechanism of loop formation remained unanswered [21]. Most recent theoretical model of knitted loops is based on adoption of 'elastica' geometrical shape, a shape that a slim body such as a uniform elastic rod will assume when buckled by action of forces [21,23].

Initial theoretical estimation of knit composite tensile behavior by numerical models using rule of mixture and orientation efficiency factor provides realistic elastic modulus estimation along the load direction but is ineffective in analyzing shear modulus or Poisson's ratio since it ignores the loop intersections [24]. The loopy nature of the yarn in the preform and 3-D architecture of the loop renders the preform heterogeneous, thus complicating the analytical procedure for predicting mechanical properties. Based on the analytical method using knitting geometrical model proposed by Leaf and Gaskin [22], theoretical estimation of mechanical properties of weft knit reinforced composites have been attempted [25,26]. Prediction of mechanical properties of plain knit reinforced composite considering the fiber content and knitting parameters have shown reasonable agreement with experimental data in which a volume averaging scheme was applied to obtain compliance/stiffness matrix of the unidirectional (UD) knitted fabric   -

composite [25]. A hexagonal mechanical model of plain weft knit fabric has been proposed for analytical modeling considering the slippage effect onto the crossover region of the unit cell model, to predict the deformational and mechanical properties of weft knitted preforms. The estimated results correlate well with the experimental data which could be applied to study and condition the deformed knit preform on a mold in the resin transfer molding (RTM) process [27].

A new micromechanical model [28,29] based on same knitted geometrical model involves a two step approach wherein an assumed representative volume element or unit cell is fractioned into many sub-cells. Representative volume element or the unit cell of preforms are the basic repeating units of the structure and among many methods of general structural geometrical methods [30], an automated algorithm has been proposed to generate the geometrical unit cells of knitted structures considering the heterogeneity of the structure [31]. These infinitely divided sub-cells are analyzed by micromechanical techniques and the values are converted into global coordinates from local coordinates by tensor transformation. An overall bridging matrix or stiffness/compliance matrix of the unit cell is obtained by averaging scheme. Adoption of a Leaf and Gaskin knit geometrical model into micromechanical technique considers the influence of knitting parameters and estimation of elastic properties of knit composites. Predictions of elastic properties of knit reinforced composite by such a method have yielded optimistic limits for warp knit preforms [32].

An attempt to compare eight different micromechanical modeling schemes available for knitted composite stiffness and strength analyses on glass fiber reinforced epoxy resin for single ply plain knit structure have been carried out. Amongst them the homogenized Reuss method and Ruan-Chou approach were most promising for strength and stiffness predictions [33]. Further improvement by incorporating the bridging model for estimating elastic constants has proved to be successful for composite stiffness prediction and it could be extended to estimate strength and inelastic composite properties [34]. Fatigue strength of carbon fiber reinforced epoxy composites with five different stacking arrangement of four layer plain knit preform has been predicted by a combination of classical laminate theory and bridging model of the same [35]. The predicted laminate fatigue strength values were found to be reasonably reliable with respect to experimental values.

KNITTABILITY AND FIBER DAMAGE DURING KNITTING

In context of advanced composite structures, high performance fibers and their interactions with the knitting process are of vital importance.

High performance yarns can withstand the bending curvatures of the knitting process; however, the simultaneous application of both bending and tensile force would cause some filaments to break at a load which is lower than the tensile strength of the yarn. It is observed that knittability of high performance yarn depends on frictional properties, bending, stiffness, and yarn strength [36]. Brittleness, high stiffness, and high coefficient of friction of such yarns [37], require low tension during yarn input, fabric take down tension setting, and loop length control by stitch cam setting for knitting. Also knittability of high performance yarns mainly depends on yarn to metal friction characteristics [38,39].

Positive yarn feed control system for knitting offer better results by applying desired yarn input tension thus reducing yarn breakage rate beside solving handling difficulties [40]. Similarly tension compensator at the feeder improve knitted preform dimensional stability. Increase in yarn tension during knitting increases fraying thereby promoting fiber bridges which could sometimes marginally improve the mechanical performance of the composites manufactured from those preforms [41]. Minimal metal to yarn contact and polished metal surfaces at yarn contact reduce yarn damage that might be incurred due to abrasion. It has also been investigated from the photographic methods that most of the filament breakage occurs at the top arc of the stitches and the broken filaments project from the fabric plane like small barbs [36].

Fibers are required to bend over sharp radius and manicure sharp corners in order to form the knitted loop in the structure. Yarn bending rigidity and inter yarn co-efficient of friction are very important determinants for loop shape while the loop length from high performance yarns and glass in particular is found to vary with needle diameter, stitching cam setting and machine setting [41]. When yarn is in contact with knitting elements, frictional parameters influence yarn tension according to the Euler's capstan equation [42]. Friction is generated due to movement of yarn and its abrasion with needles and knitting elements.

Although high tenacity of high performance yarn indicates better knittability, coupled effects of lower surface strains, large tension buildup in the yarn, low out-of-plane properties, and fiber damage due to primitive tension failing are serious impediments to the knittability of high performance yarn [41].

Yarn hairiness induced due to surface fiber structure because of yarn abrasion with knitting elements would also result in fiber damage affecting knittability [36]. Table 1 [6] illustrates the combinational stresses to which the yarn is subjected to while performing, indicating that the knitting process involves four types of stress in comparison to others but the severity of these stresses during their manufacture also relates to the knittability.

Table 1. Combinations of stresses to which yarns are subjected during preforming [6].

	Surface stress	Tensile stress	Compressive stress	Bending stress	Shear stress	Torsional stress	Impact stress
Weaving							
-warp	x	x	x	x	–	–	x
-weft	x	x	x	x	–	–	x
Knitting	x	x	x	x	–	–	–
Braiding	x	x	x	x	–	x	–
Sewing	x	x	x	x	x	–	x

(x: stress presence, – stress absence).

STRUCTURAL MODIFICATION IN KNITS FOR COMPOSITE APPLICATION

Certain techniques are possible during the knitting action, which can radically change the physical appearance and properties of a knitted construction. Four of such main techniques are laying-in, plating, open work and plush–pile constructions amongst which the laying in technique has been explored and proven successful [10]. An in-laid structure consists of a ground structure of knitted yarns which hold in position other non knitted yarns which were incorporated into the structure during the same knitting cycle to modify one or more of fabric properties like strength, stability, weight, handle, etc. [43,44].

DIRECTIONALLY ORIENTED KNITTED PREFORMS

Knitted fabrics are considered 3-D due to non-planar configuration of the loops in the structure. Planar 2-D images of knitted structures would not provide the truthful geometric definition of the structure, given such scenario, 3-D image analysis would be critical from the point of view of realistic finite elemental analysis of composite material performance. Ozer [45] has developed computer simulation of warp knitted structures considering the yarn loop shape control points, loop knot sequence, and order of the loop curve. Isotropic and poor mechanical properties of knitted fabrics have lead to structural modifications with inlay yarns in horizontal (weft), vertical (wale), and diagonal directions to develop preforms suitable for the composite applications.
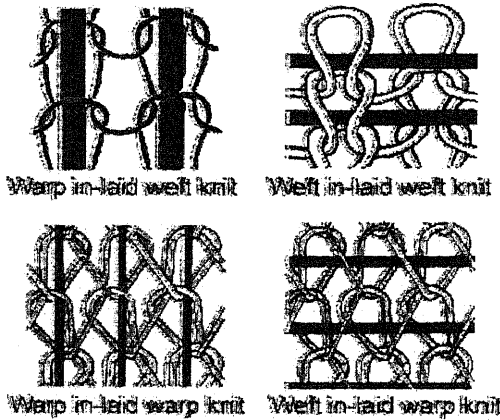
FIGURE 2. Unidirectional knitted structures.

Unidirectional Knit Structures

Monoaxial structures such as warp or weft knits with inlay yarn in any one particular direction are termed as UD knitted fabrics. Inlay insertion across the width of knitted structure, also known as weft insertion, is a form of inlay extending over the entire width of the fabric. In weft knitting, inlaid yarns are trapped inside double needle bed fabrics. 1 × 1 Rib structured inlaid preforms have been attempted and found that UD strength can be enhanced substantially in the inlaid directions [13,46] and composites in such cases with better tensile strength compared to standard woven counterparts have been reported [47,48]. Magazine return weft insertion and single-end magazine weft insertion are the two principles on which weft insertion during warp knitting takes place. Weft inserted warp knit preforms have been characterized for composite applications [56]. Figure 2 illustrates the UD knit structures, weft inserted rib structure, warp inlaid weft knit, weft inlaid warp knit, and warp inlaid warp knit structures for composite applications.

Biaxial Knit Structures (2-D Knits)

Incorporation of additional yarns in two directions in the knitted structures is termed as biaxial knitted structures. Introduction of both weft or warp yarns or diagonal yarns into warp and weft knitted fabrics during knitting process combines the advantages of woven and knitted fabrics together [57]. Co-we-knits is a combined weaving and knitting

Welt knit (in-lays 0/90)   Warp knit (in-lays +45/-45)   Warp knit (in-lays 0/90)
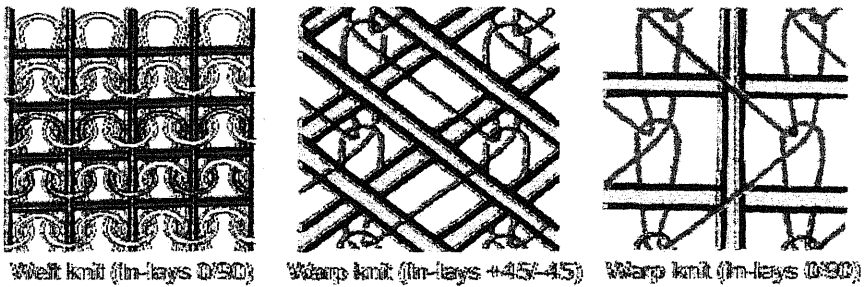
FIGURE 3. Biaxial knitted structures [16,64].

technique, which is a modification of the warp knitting technique, wherein weft yarn is laid in front of warp threads to simulate woven and knitted structures together [10,16]. Warp laying in warp knits is either by miss lapping or with the use of the fall plate technique [18]. Figure 3 [16,18] illustrates biaxial structures—warp and weft in-laid weft knit, warp and weft in-laid warp knits, and diagonally yarn inlaid knit structures.

Multiaxial–multilayer Knitted Structures (3-D Knits)

Multiaxial–multilayer structures are fabrics bonded by a loop system, consisting of one or several yarn layers stretched in parallel. Multiaxial–multilayer warp knits (MWK) are also termed as non-crimp structures since the presence of knitted loops is to perform the function of holding layers of uncrimped inlay yarns. These yarn layers may have different orientation and different yarn densities of single ends. Multiaxial–multilayer fabrics are used to reinforce different matrices since combination of multidirectional fiber layers and matrices has proved capable of absorbing and distributing extraordinarily high strain forces. Among three basic types of these structures, Karl Mayer structures [16] are those in which along with the ground tricot structure, in-laid yarns in warp, weft, and both diagonal directions (30–60°) are incorporated in the fabric. Two other types the Liba and Malimo systems along with layers of knits, can also incorporate fiber/nonwoven fleece between the layers to produce multiaxial–multilayer structures [58], which are predominantly applied for composite reinforcements. Figure 4 illustrates tricot and chain stitched multiaxial–multilayer knitted structure along with the cross-sectional view of the same. Structural and mechanical studies on these knit preforms based on unit cell modeling have shown superior performance of these preforms for composite applications [59–62].
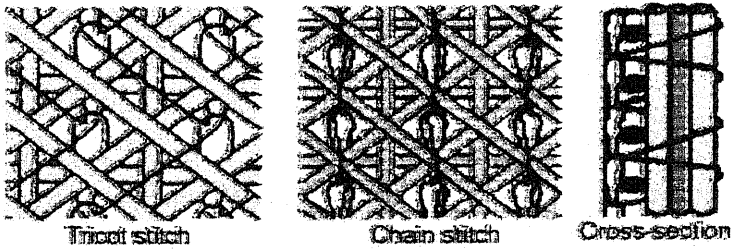
Tricot stitch   Chain stitch   Cross-section

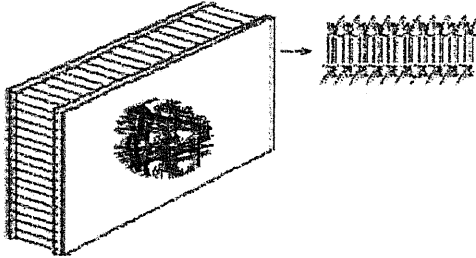FIGURE 4. Multiaxial–multilayer knitted structure.

FIGURE 5. Spacer fabric [16].

Studies on experimental characterization of composite materials reinforced with 4-ply multiaxial knitted carbon fabrics compared with conventional prepreg tape composites indicate that high quality knitted carbon fabrics can be produced and RTM can be used to produce aerospace quality composite materials. Tension and compression strength reductions for the multiaxial knitted fabric composites ranged from 20% to 30%, compared to prepreg tape laminates. However, the knitted fabric composites exhibited compression after impact strengths up to 80% higher than the strength of comparable prepreg tape laminates [63].

Composite Knitted Structures

The purpose of composite knitted fabrics is to combine different materials of partly opposite properties with knitting to create a single membrane that performs better than its individual components. With the Raschel warp knitting and stitch-bonding machines, the composite fabric is produced in a single, simple, and very productive operation. Spacer knitted fabrics (Figure 5) are sandwich structures with fabric thickness upto 60 mm, manufactured from a two needle bar Raschel warp knitting machine with four guide-bars [16]. Generally utilized for technical textiles, it has high potential as preform for composite applications.

Stitch knit fabrics also produce sandwich structures with the aid of tricot stitches, wherein layered fabrics are stitched together to produce sandwich preforms. Stitching has long been known to have important uses in enhancing the strength and damage tolerance of composite structures [63]. Stitching by Kevlar threads would enhance the structural integrity and damage tolerance of thin carbon/epoxy composite structures, but attempts to stitch thick prepregs revealed serious limitations to the method [64]. The most popular composite knitted fabric is a bi-axial reinforced nonwoven (Figure 6). These structures are frequently used as substrate for laminating or in the field of geotextiles as geocomposites [16].

Stitching-through principle of making warp knitted multiaxial–multilayer structures (Figure 7) for fiber reinforced composites ensures isotropic behavior through uniform distribution of yarn ends in multidirections [63]. Due to the noncrimped and parallel yarn sheets in them, they are particularly suitable for fiber reinforced composites with special characteristics such as low specific weight, adjustable stiffness between extremely stiff and extremely stretchable, and highest mechanical load resistance [65].
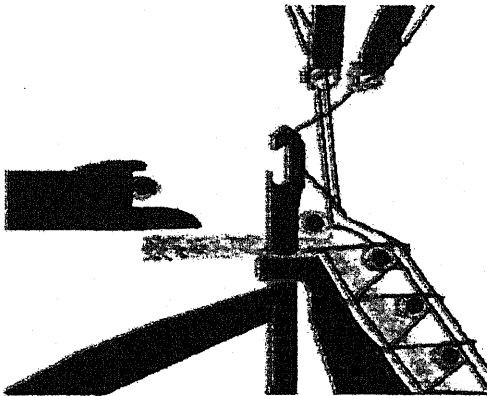

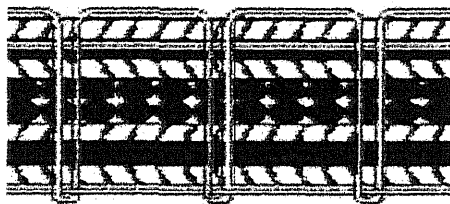**FIGURE 6.** Bi-axially reinforced nonwoven composite fabric [16].

FIGURE 7. Knit-stitched structure [64].

Stitch-bonding is considered to be a special case of stitching with the warp knitting technique while the loop formation cycle is similar to warp knitting but deviates with respect to constructive design of the stitch-bonding area (horizontal needle arrangement, fixed retaining, backing rail), needle types applied (stitching needle), reference size for machine gauge (number of needles per 25 mm), and conversion of unbonded fibrous webs to purely mechanically stitch-bonded nonwovens [16].

PROPERTIES OF KNITTED PREFORMS AND THEIR COMPOSITES

Knitted preforms, compared to woven counterpart are considered thick, highly extensible, distribute the stress better throughout the structures, and have less flexural rigidity [5]. The complex nature of the knitted structures generally do not exhibit distinct directions where the strength is at maximum, but the knit preform properties are greatly influenced by the fiber strength, modulus, knitted structure, stitch density, number of knitted fabric plies, pre-stretch parameters, inlays, and other knitting parameters [66].

Deformation behavior of knitted preforms can be predicted by initial load-elongation properties of knitted fabrics. A theoretical model based on elastica theory was analyzed for load–extension properties of plain weft knits made from high performance yarns for composite applications. Assuming that plain knitted fabrics were made of frictionless, inextensible, incompressible naturally straight filaments, knitted fabric formed with planar loop structures with any two loops at adjacent courses interlock in such a way that yarns are fully in contact at the cross regions and the reaction forces at the loop interlacing region (Figure 8) were simplified as concentrated force [67]. Based on the theoretical calculations, the force (P) acting on point C is equated by the loop function angle (C_4) and loop length (L) as given by

$$P = 16(C_4)^2 L^2 \tag{1}$$

Force corresponding to stress along the coursewise direction (T) is influenced by the point force (P) at C and the loop angles (β and γ) as per the Equation (2)

$$T = -P[\sin(\gamma) \cdot \tan(\beta) + \cos(\gamma)] \tag{2}$$

The yarn disposition along the curvature ABC along with the point force and loop angles regulate bending moment parallel to the X-axis as shown in
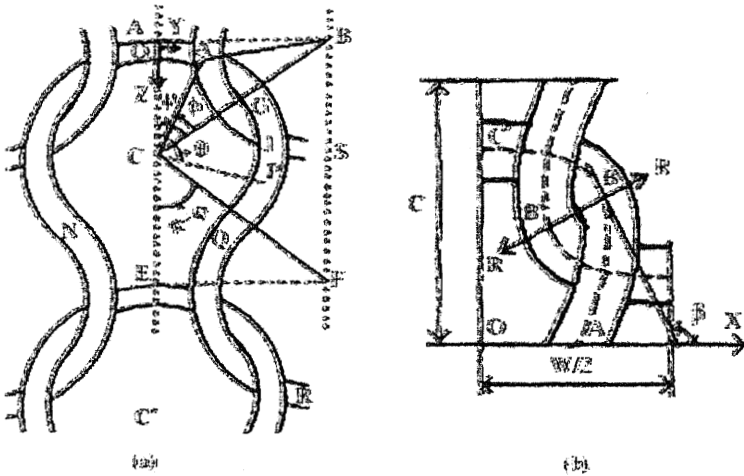
FIGURE 8. Unit structure of plain weft knitted fabric. (a) loop [22] and (b) intersection of loop [6].

Equation (3). Bending rigidity of yarn (B) is governed by force (P), loop angles and the stress along the Y-axis as given in Equation (4).

$$M = P[Y''_{AB} + Y_{BC}(\sin(\gamma) \cdot \tan(\beta) + \cos(\gamma)] \tag{3}$$

$$B = \frac{(T_Y + M)}{(\mathrm{d}\theta/\mathrm{d}s)} \tag{4}$$

Theoretical calculations of tensile properties with the above equations were carried-out and compared with the Shahnan and Postle [68] analysis and experimental data have given good agreement with actual performance (Figure 9) of plain weft knit fabric made from high performance fibers. Shahnan and Postle's prediction of plain knitted fabric load–extension behavior under uniaxial stress in coursewise direction provided realistic estimation but was difficult to apply due to complexity.

The Expression (5) for warp knitted fabrics for initial load–elongation [69] is given as,

$$\text{Load/unit width} = \frac{2AE(k)^2 \cdot F(\theta)}{(c + d)^2 \cdot w} \tag{5}$$

where, $F(\theta)$ is a function of strain, E is Young's modulus of material, and Ak^2 is moment of area of cross section of material. This estimation is valid up to 15% extension, beyond which the structure begins to break
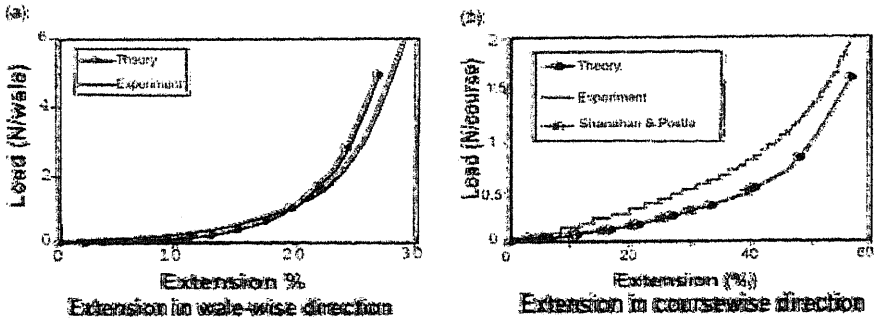
FIGURE 9. Theoretical and experimental load – Extension curves of plain knitted perform [63]. (a) Extension in wale-wise direction; and (b) Extension in course-wise direction.
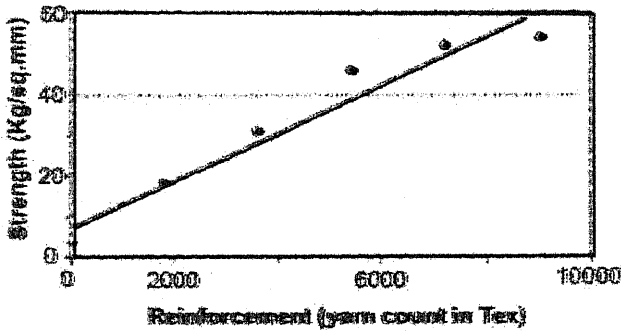

FIGURE 10. Variation of tensile strength of differentially glass reinforced rib knit epoxy composites [48].

down when reaching maximum extension nearly twice that predicted by Equation (5) [69].

Strength and stiffness of the knit reinforced composite is considered relatively lower than woven and braided textile preformed composites [70]. This reduced performance of knit preforms has been attributed to the curved fiber orientation in the loops due to which fiber strength and stiffness is not completely availed in preformed composite performance.

Improved tensile properties with structural modification of knit preforms have been attempted [47,48]. 1 × 1 Rib glass knit preformed composites reinforced with epoxy resin prepared by the RTM technique with varying inlay yarns to develop strength enhanced UD composite have been successful. Figure 10 illustrates the tensile strength behavior of such laminates which attained more than 25% UD strength compared to standard woven preformed composites ($40 \, kg/mm^2$ at 0.65 V_f) [48].

A new class of knitted composites has been designed to maximize the total energy absorbed during tensile failure [49]. Knitted loops of light, continuous fiber tows are configured in such a way that they must be drawn through relatively large displacements before they come into direct contact with one another. Upon loop contact, the material hardens locally, forcing further damage to develop by the same process elsewhere. In this way, the entire gauge section absorbs energy before ultimate failure. The mechanisms involved in damage delocalization and failure are detailed and modeled in a simple manner.

The mode I inter-laminar fracture toughness of advanced knitted textile composites was investigated [50]. Two complex weft-knitted glass fabrics were selected for the study: a triple rib knit and a Milano knit were impregnated with a tough epoxy resin and tested using a double cantilever beam geometry. For both knitted composites, the influence of the growth direction was studied by investigating crack propagation in both the wale and course directions. The results clearly showed that knitted fabric composites have exceptional inter-laminar fracture toughness properties, namely, more than $7000 \, J/m^2$. The 3-D loop structure induces various energy consuming mechanisms, which do not occur in other composites. Toughening mechanisms such as crack branching, friction, yarn bridging and breakage were identified using scanning electron microscopy.

The trade-off effect between loop length or stitch density with regard to the in-plane tensile and impact behavior of weft-knitted textile composites have been studied [51]. Three different styles of weft-knit structures, Milano, 1×1 rib and plain knit, were investigated. It is interestingly noteworthy that an increase in loop length or stitch density has the opposite effects on the tensile strength and impact performance of the weft-knitted composites.

Impact damage characteristics of plain weft-knitted carbon fabric reinforced epoxy composites subjected to low-velocity impact had been examined [52]. The results showed that matrix cracking, matrix/fibre debonding, and fibre breakage were the major damage mechanisms and they came in the form of crossed cracks in the matrix on the surfaces of specimens and debonding of matrix/fiber along the cracks in C-scan images. This type of composite exhibited good energy absorption capacity as its energy absorption ratio can reach as high as 80%. Weft knitted glass fiber (GF) reinforced poly(ethylene-terephthalate)(PET) crash elements were tested under dynamic loading to gain insight in the response of knitted GF/PET parts and to demonstrate the energy absorption potential [53]. Tests on SMC, GMT, UD-reinforced GMT, and woven fabric were performed for comparison with the knitted reinforcement. The crash characteristics of the investigated knitted fabrics were between those of random oriented composites and directional oriented composites.

The mechanical response of weft knitted carbon fiber (CF) and GF fabric-reinforced thermoplastic composites with polyetheretherketone (PEEK) and polyethyleneterephthalate (PET) was studied by dynamic-mechanical thermal analysis (DMTA) and static tensile tests [54]. A strong anisotropy was observed in both stiffness and strength when the specimens were loaded in wale (stronger) and course direction (weaker) of the knit, respectively. The anisotropy factor was estimated by considering the relation of the loop numbers in the course and wale direction that resulted in good agreement with the experimental data.

The mechanical response of knitted GF and CF fabric-reinforced polyamide-12 (PA-12) composites was compared both under static (tensile, flexural) and dynamic (perforation impact) conditions [55]. The GF- and CF-content of the composites produced by hot pressing of 8 layers of planar weft knits containing staple reinforcing GF or CF and PA-12 fibers was practically the same, viz. ca 50 vol%. Dynamic-mechanical thermoanalysis (DMTA) showed a strong stiffness anisotropy: the stiffness of the composites in the wale-direction was markedly higher than in the course-direction. The same strong anisotropy was also found for the static tensile and flexural characteristics (stiffness and strength). The mechanical performance of the knitted CF-reinforced composite was superior to the GF-reinforced version under dynamic perforation impact conditions as well.

Compressibility of knitted preforms is of importance in the RTM process, wherein mold closing force and attainable fiber volume fraction is directly dependant on the fabric compressibility. Knitted structures are highly compressible compared to wovens and it is observed that multilayered knitted preforms are easier to compress than the single layered, since the loops of different layers can mingle into each other in multilayered preforms [71]. Compression behavior of knitted composites are mainly governed by the reinforcing matrix, hence this property is much more isotropic and predictably knitted composites perform better in compression than in tension [72].

The behavior of knit reinforced composite materials under impact loading is complex and is generally not well understood. Knitted composites have typically small damage areas demonstrating good resistance and a failure zone geometry of near circular (Figure 11) due to their higher isotropic behavior as compared to UD or woven composites. In the case of knitted structures, because of the looped configuration of the reinforcing fibres, the structure is more isotropic. The variation in impact damage resistance of different knit structures with varying knit parameters is very minimal implying that knits in general greatly enhance the structural integrity of the composites, giving rise to an improved interlaminar fracture toughness value resulting in better impact energy absorption [73]. In comparison with the
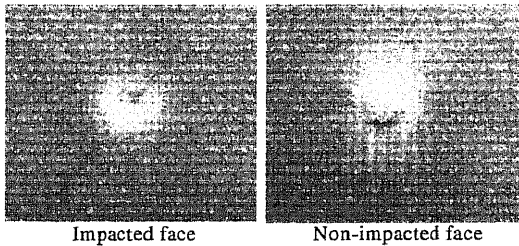
| Impacted face | Non-impacted face |

FIGURE 11. Typical example of impact damage to plan knitted composite specimens (energy level 8.18 J/mm) [68].

braid, uni-fabric, and prepreg tape composites, knitted structures show superior retention of compressive strength after impact event. Compression after impact (CAI) strengths were decreased by only 12% for the knitted fabric in the given impact energy range, whereas the equivalent woven fabric CAI values fell by up to 40% [74]. Khondker et al. [73] argued that this demeanor pertained to greater damage resistance during the impact event to more homogeneous distribution of knitted reinforcement in the matrix, resulting in a better ply nesting and intermingling of knitted loops within the fabric layers, thus suppressing the propagation of crack or delamination growth.

The knitted preforms have high drapability and deformability under low load, the ability because of which complex contouring of shapes are possible with uniform fiber volume fraction throughout the composite material and in certain cases it is possible to develop truly 3-D fabrics that do not need any seaming when put in the mold [75]. Formability studies on two-biased multiaxial warp knit during hemisphere-pressing process based on the deformation behavior has been done to predict possible wrinkles, local deformations, and the flat shape for hemisphere. The comparison between theory and experiment suggest that the model fit the results very well [76]. Net shape performing is another way to knit the structure to the desired shape and size to fit the composite requirement. The property of deformability and net-shapability of knitted preforms is utmostly significant when composite panels with holes are to be designed. Such composites with holes display higher notch strength and bearing properties than drilled composites due to better dissipation of stresses away from the hole through looped network of knitted preforms [77,78].

The relationship between the physical, mechanical, and simulated formability properties of weft-knit GF preforms were studied by Savci et al. [79]. The results for the full Milano structure showed that the plain loop length and tensile properties enabled a good prediction of simulated formability. It also investigates the effects of different knit structures on the deformation of weft-knit preforms. The other structures examined include

the alternating half Milano, full Milano, French double pique, and full cardigan. The results indicate that irrespective of structure, the loop length and tensile properties determine the simulated formability of weft-knit preforms.

This ability to form 3-D shapes using the biaxial extensibility of knitted structures enables these knitted textile materials to be utilized for a wide variety of close fitting apparel garments and shaped composite preforms. Some representative biaxial extension curves for the plain knitted structure are described in a paper by Postle [80]. These curves illustrate an unusual shape for the load–extension curve of a textile material arising from pre-tension or pre-stress. The pre-stress yields an initial high tensile modulus for the structure in contrast to the very low initial modulus characteristic of apparel textiles. Accordingly, for knitted textile materials, it is shown how biaxial extension of the fabric introduces a fabric pre-stress to maximise the 3-D fabric formability especially when subjected to transverse compression by the resin or matrix in a composite material.

Sandwiches based on stampable foam core and face sheets offer potential for cost-effective applications. Since the formability of such sandwich structures mainly depends on the drapability of the face sheets, the deformation behavior of several types of textile preforms was evaluated [81]. Drapability tests were performed on several woven and knitted fabrics in order to relate the forming energy to the preform architecture. Due to their high drapability and low forming energy, warp-knitted structures were selected as textile reinforcement for the sandwich face sheets.

The effects of deforming knitted fabrics on the tensile and compressive properties of their composites have been investigated for the weft-knit Milano rib fibre architecture [82]. The properties have been studied for both the course and wale directions for composites with fabrics deformed in either of the two directions. It was found that any change in the mechanical properties of the deformed composites with respect to their undeformed counterpart is strongly related to the changes in the knit structure brought about by the induced deformation to the knitted fabric. Deformation in the knitted fabric also affects the tensile fracture mode whereby increased deformation, be it wale- or course-wise, transforms transverse fracture to shear fracture in either loading axis. On the contrary, the compressive fracture mode is insensitive to fabric deformation.

Permeability of preform in the RTM process is an important parameter facilitating the setting of proper processing conditions by determination of optimal gate and vent locations. In-plane permeability of fibrous preforms have been investigated based on tracking the time with variation of flow front when a liquid is injected into the mold with a transparent mold top to show the flow front or sensors for flow front detection [83,84]. A method for
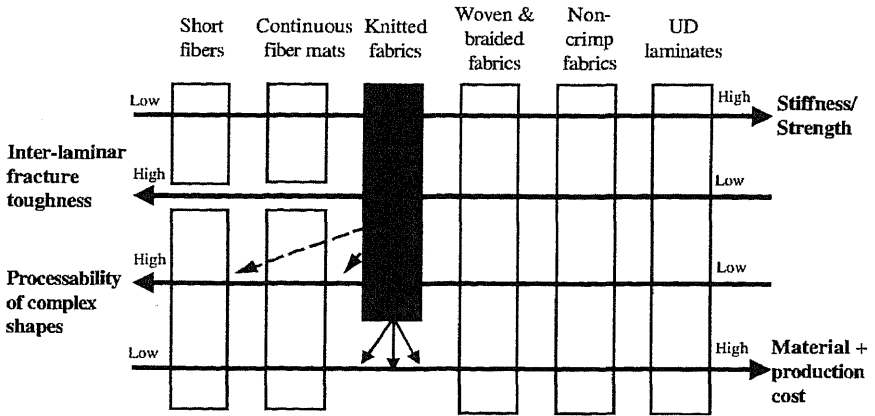
| Short fibers | Continuous fiber mats | Knitted fabrics | Woven & braided fabrics | Non-crimp fabrics | UD laminates |

Low ⬛⬛⬛ High → **Stiffness/Strength**

Inter-laminar fracture toughness High ⬛⬛⬛ Low

Processability of complex shapes High ⬛⬛⬛ Low

Low ⬛⬛⬛ High → **Material + production cost**

FIGURE 12. Overview and comparison of some properties of existing reinforcements [70].

Table 2. *Directional behavior of knitted fabrics in unjammed configurations [6].*

Construction	Directional stability			Directional conformability			Directional extensibility			In-plane shear resistance		
	a	b	c	a	b	c	a	b	c	a	b	c
Weft knit				x	x	x	x	x	x			
Weft in-laid weft knit		x		x		x						
Warp in-laid weft knit	x				x	x						
Weft knit in-laid warp and weft	x	x				x						x
Warp knitted				x	x	x	x	x	x			
Weft in-laid warp knit		x		x		x						
Warp in-laid warp knit	x				x	x						
Warp knit in-laid warp and weft	x	x				x				x	x	x
MWK ±45°			x	x	x					x	x	
MWK 0/±45°	x		x	x						x	x	x
MWK ±45/90°			x	x	x					x	x	x
MWK 0/±45/90°	x	x	x							x	x	x

(a: machine direction, b: crosswise direction and c; bias direction, x: behavior, presence).

determination of the same has been developed by gas flow and applied for knitted preforms [85].

Figure 12 presents the overall status of knitted preforms against other existing textile reinforcements with respect to strength/stiffness, toughness, contouring, and production costs [70]. The various knitted structural parameters of dimensional stability, extensibility, conformability, and in-plane shear resistance as given in Table 2 [6], provide an estimation of knitted fabric shapability and contourability. It is interesting to note that

contourability which is governed by conformability and extensibility does not always yield mechanical properties which is influenced by stability and shear resistance. A balance between the two has to be approached while designing preforms of desired characteristics.

APPLICATIONS OF KNITTED PREFORMS FOR COMPOSITE MATERIALS

Among many applications of knitted preforms for composites, major fields include transportation, aerospace, medical, and civil applications. Multiaxial warp knit preform for top shell composite and an interlock weft knit preform inlaid with additional yarn in horizontal direction for the wheel wells of an all-composite electrical vehicle was achieved by a combination of shaping techniques: holding, narrowing, widening, and binding off to obtain sufficiently high fiber volume fraction and mechanical strength from the curved fibers in the knitted loops [13]. Vehicular crash guards, composite helmet by net shaping, and contouring [86] and railway coaches of non crimped knitted reinforced composites [87] are the other major automobile applications.

A warp knitted composite material formed by a base net structure embedded with silicon carbide deposits has been successfully implemented as abrasive composite material for finishing activities in building materials and nonwoven filter fabrics [88]. The complicated nature of the short weft knitted preforms enhance bonding and mechanical anchoring to the cement matrix effecting higher efficiency factor of flexural strength [89]. T-joints and T-shape connectors [90], cones, pipes, and I-beams [91] form supplementary civil applications.

Varistor of surge arresters to protect the electrical equipments has been tried with knitted E-glass/PP thermoplastic composite material [92]. Knitted ceramic composite jet engine vanes impregnated with silicone carbide by chemical vapor deposition [93], radomes, rudder tip fairing for midsized jet engine aircraft [69], medical prostheses made from glass and Kevlar knitted composites [94,95] and electrically conductive composites, made from copper wire/glass fiber knit fabric reinforced with polypropylene polymer matrix [96] are a few important composite applications worth mentioning.

CONCLUSIONS

Knitted preforms are particularly suited for the rapid production of composite components with complex shapes due to their low resistance to

deformation and minimum material wastage. At the same time knits consume more yarn for comparable fabric properties against wovens, which is of much concern since cost of yarn much exceeds cost of fabric production particularly for high performance fiber preforms for composite applications. Multidirectional knitted preforms are in its embryonic stage and would be preferred preforms due to better performance characteristics. It is evident that the knitted preforms perform better than the existing ones in terms of cost, contourability, and impact strength but tensile, bending strength lacks need to be compensated with structural modifications as mentioned earlier. With suitable structural modifications and very high versatile design potential, knitted preforms offer a good deal for composite applications.

ACKNOWLEDGMENTS

REFERENCES

1. Hull, D. (1982). *An Introduction to Composite Materials*, Cambridge University Press, Cambridge, UK.
2. Dewalt, P.L. and Reichard, R.P. (1994). Just How Good are Knitted Fabrics, *Journal of Reinforced Plastics and Composites*, **13**: 908–910.
3. Hearle, J.W.S. (1994). Textiles for Composites a Business Opportunity for the 21st Century Part I, *Textile Horizons*, **14**(6): 12–15.
4. Vinayak Ogale and Alagirusamy, R. (2004). Textile Preforms for Advanced Composites, *Indian Journal of Fiber and Textile Research*, **29**(9): 366–375.
5. Jones, F.R. (1994). *Handbook of Polymer-fiber Composites*, Polymer Science and Technology Series, Longman, UK.
6. Chou, Tsu-Wei and Ko Frank, K. (1989). *Textile Structural Composites*, Elsevier Science, Amsterdam.
7. Harrocks, A.R. and Anand, S.C. (2000). *Handbook of Technical Textiles*, Textile Institute, Woodhead Publishing limited, UK.

8. Mayer, J., Joop, De Haan, Reber R. and Wintermantel, E. (1999). Knitted Carbon Fiber Reinforced Thermoplastics: Structure-properties Relations, *Material Science Research International*, **5**: 143–150.

9. Surya, D., Pandita, Falconet D. and Verpoest, I. (2002). Impact Properties of Weft Knitted Fabric Reinforced Composites, *Composites Science and Technology*, **62**: 1113–1123.

10. Leong, K.H., Ramakrishna, S., Huang, Z.M. and Bibo, G.A. (2000). The Potential of Knitting for Engineering Composites, *A Review, Composites: Part A*, **31**: 197–220.

11. Ajgaonkar, D.B. (1990). *Knitting Technology*, Universal Publishing Corporation, Mumbai, India.

12. Demboski, Goran and Bogoeva-Gaceva, Gordana (2001). Properties of Weft Knitted Composites Affected by Preform Stretching, *Applied Composite Materials*, 8(6): 371–384.

13. Aart W. Van Vuure and Ko Frank, K. (2003). Net Shape Knitting for Complex Composite Preforms, *Textile Research Journal*, 73(1): 1–10.

14. Huang, Z.M., Ramakrishna, S. and Andrew, A.O. Tay (1999). A Micromechanical Modeling Approach to the Mechanical Properties of Textile Elastomeric Composites, *Journal of Society of Material Science*, Japan, Special Issue on Recent Advances of Composites in Asia and Australasia, 5(3): 189–195.

15. Leong, K.H., Falzon, P.J., Bannister, M.K. and Herszberg, I. (1998). An Investigation of the Mechanical Performance of Weft-Knit Milano-Rib Glass/Epoxy Composites, *Composites Science and Technology*, **58**: 239–251.

16. Raz, S. (2000). *The Karl Mayer Guide to Technical Textiles*, Karl Mayer Textilmaschinenfabrik, Germany.

17. Yoon, Hye-Shin and Park, Shin-Woong (2002). Determining the Structural Parameters that Affect Overall Properties of Warp Knitted Fabrics using Cluster Analysis, *Textile Research Journal*, 72(11): 1013–1022.

18. David, J. Spencer (2001). *Knitting Technology*, Woodhead Publishing Limited, ISBN 1855733331, UK.

19. Brackenbury, Terry (1992). *Knitted Clothing Technology*, Blackwell Science, UK.

20. Pierce, F.T. (1937). The Geometry of Cloth Structure, *Journal of Textile Institute*, **28**: T45.

21. Hearle, J.W.S., Grosberg, P. and Backer, S. (1969). *Structural Mechanics of Fibers, Yarns and Fabrics*, John Wiley Interscience, UK.

22. Leaf, G.A.V. and Glaskin, A. (1955). The Geometry of a Plain Knitted Loop, *Journal of the Textile Institute*, **45**: T587–605.

23. Munden, D.L. (1959). The Geometry and Dimensional Properties of Plain Knit Fabrics, *Journal of the Textile Institute*, **50**: T448–471.

24. Rudd, C.D., Owen, M.J. and Middleton, V. (1990). Mechanical Properties of Weft Knit Glass Fiber/Polyester Laminates, *Composite Science and Technology*, **39**: 261–268.

25. Ramakrishna, S., Huang, Z.M., Teoh, S.H., Tay, A.A.O. and Chew, C.L. (2000). Application of the Model of Leaf and Glaskin to Estimating the 3D Elastic Properties of Knitted Fabric Reinforced Composites, *Journal of Textile Institute*, 1(1): 132–150.

26. Ramakrishna, S. and Hull, D. (1994). Tensile Behavior of Knitted Carbon Fiber-fabric/epoxy Laminates - Part II: Prediction of Tensile Properties, *Composite Science and Technology*, **50**: 249–261.

27. Gowayed, Y.A. (1992). An Integrated Approach to the Mechanical and Geometrical Modeling of Textile Structural Composites, *Doctoral Thesis*, NCS University, USA.

28. Ruan, X.P. and Chou, T.W. (1996). Experimental and Theoretical Studies of the Elastic Behavior of Knitted-fabric Composites, *Composite Science and Technology*, **56**: 1391–1403.

29. Ming Zheng, Huang, Ramakrishna, S. and Tay, A.A.O. (1999). A Micromechanical Approach to the Tensile Strength of the Knitted Fabric Composite, *Journal of Composite Materials*, 33(19): 1758–1791.

30. Lomov, S.V., Huysmans, G. and Verpoest, I. (2001). Hierarchy of Textile Structures and Architecture of Fabric Geometric Models, *Textile Research Jounal*, 71(6): 534–543.

31. Robitaille, F. Long, A.C., Jones, I.A. and Rudd, C.D. (2003). Automatically Generated Geometric Descriptions of Textile and Composite Unit Cells, *Composite: Part A*, **34**: 303–312.

32. Gommers, B., Verpoest, I. and Van Houtte, P. (1998). Analysis of Knitted Fabric Reinforced Composites: Part II, Stiffness and Strength', *Composites: Part A*, **29**: 1589–1601.

33. Ming Huang, Zheng and Ramakrishna, S. (2000). Micromechanical Modeling Approaches for the Stiffness and Strength of Knitted Fabric Composites: A Review and Comparative Study, *Composites: Part A*, **31**: 479–501.

34. Huang, Z.M., Ramakrishna, S., Tay, A.A.O., Teoh, S.H. and Chew, C.L. (1997). A New Modeling Procedure for Estimating the Elastic Moduli of Knitted Fabric Composites, In: *Proceedings of 5th Japan International SAMPE Symposium*, Tokyo, pp. 719–724.

35. Ming Huang, Zheng, Ramakrishna, S. and Aye Thwe, Aye (2002). Modelling and Characterization of Fatigue Strength of Laminated Composites with Knitted Fabric Reinforcement, *Journal of Composite Materials*, 36(15): 1781–1801.

36. Lau, K.W. and Dias, T. (1994). Knittability of High-modulus Yarns, *Journal of Textile Institute*, 85(2): 173–190.

37. Hearle, J.W.S. (2001). *High Performance Fibres*, The Textile Institute, Woodhead Publishing, UK.

38. Knapton, J.J.F. (1966). The Dynamics of Weft Knitting: A Mathematical Analysis, *Textile Research Journal*, **36**: 706–714.

39. Knapton, J.J.F. and Munden, D.L. (1966). A Study of the Mechanism of Loop Formation on Weft Knitting Machinery: Part I and II, *Textile Research Journal*, **36**: 1072–1091.

40. Epstein, M. and Nurmi, S. (1991). Near Net Shape Knitting of Fiber Glass and Carbon for Composites, In: *Proceedings of 36th International SAMPE Symposium*, Covina, CA, USA, pp. 102–113.

41. Savci, S., Curiskis, J.I. and Pailthorpe, M.T. (2001). Knittability of Glass Fiber Weft Knitted Preforms for Composites, *Textile Research Journal*, 71(1): 15–21.

42. Morton, W.E. and Hearle, J.W.S. (1993). *Physical Properties of Textile Fibres*, The Textile Institute, Woodhead Publishing, UK.

43. Niklas, Svensson (1998). Textile Structures for Load-carrying Composites, *Textile Magazine*, **2**: 6–13.

44. Sarlin, J., Pentti, P. and Jarvela, P.K. (1990). A New Type of Knitted Reinforcing Fabrics and Its Application, In: *Proceedings of Fourth European Conference on Composite Materials*, London, UK, pp. 621–623.

45. Ozer, Goktepe (2001). Use of Non-uniform Rational b-splines for three-dimensional Computer Simulation of Warp Knitted Structures, *Turkish Journal of Engineering and Environmental Sciences*, **25**(4): 369–378.

46. Frank, K. Ko (1989). Three-dimensional Fabrics for Composites, *Textile Structural Composites*, Elsevier Science, Amsterdam.

47. Rao, R.M.V.G.K., Anand Nahar, G. and Alagirusamy, R. (2000). Mechanical Properties of Glass Composites Based on Knitted Preforms with Inlays, *Indian Journal of Fibre and Textile Research*, **25**(1): 115–120.

48. Padaki Naveen, V., Vani, A., Prakasha, V., Divakar, C.J., Ananth Krishnan, T. and Rao, R.M.V.G.K. (2000). Studies on Mechanical Behavior of Knitted Glass-epoxy Composites, *Journal of Reinforced Plastics and Composites*, **19**(5): 396–402.

49. Cox, B.N. and Davis, J.B. (2001). Knitted Composites for Energy Absorption under Tensile Loading, *Composites Part A: Applied Science and Manufacturing*, **32A**(1): 91–105.

50. Falconnet, D., Bourban, P.E., Pandita, S., Manson, J-A.E. and Verpoest, I. (2002). Fracture Toughness of Weft-knitted Fabric Composites, *Composites Part B: Engineering*, **33B**(8): 579–588.

51. Khondker, Omar A. (2001). Trade-off Effect of the Knit-structural Parameters on the Tensile and Impact Strength of Weft-knitted Textile Composites, In: *The Eighth East Asia–Pacific Conference on Structural Engineering and Construction: Challenges in the 21st Century: EASEC-8 [Electronic Resource]*, p. 7.

52. Yang, G., Lim, C.-T. and Ramakrishna, S. (2001). Low-velocity Impact of Weft-knitted Carbon Fabric/Epoxy Composites by a Sharp-tipped Projectile, In: *Cancom 2001: Third Canadian International Composites Conference*, 21–24 August 2001, Quebec, Canada, p. 9.

53. Huisman, M.R.S. and Maier, M. (2000). Investigation on the Crash Behavior of Knitted Glass Fibre Reinforced Poly(ethylene-terephthalate) Structures, *International Journal of Crashworthiness*, **5**(1): 79–88.

54. Karger-Kocsis, J., Ostgathe, M., Czigany, T. and Gaal, J. (1996). Stiffness and Strength Anisotropy in the Tensile Response of Weft Knitted Fabric-reinforced PEEK- and PET-composites, *Advanced Composites Letters*, **5**(3): 71–75.

55. Czigany, T. and Karger-Kocsis, J. (2001). A Comparison of the Mechanical Behaviour of Weft-knitted Glass and Carbon Fiber Fabric-reinforced Polyamide-12 Composites Produced with Commingled Staple Yarns, *Polymers and Polymer Composites*, **9**(8): 491–497.

56. Ko, F.K., Krauland, K. and Scardino, F. (1982). Weft Insertion Warp Knit for Hybrid Composites, Progress in Science and Engineering of Composites, In:

Hayashi et al. (eds), *ICCM-V, Fourth International Conference on Composites*, pp. 982–987.

57. Godou, U., Diestel, O. and Offermann. P. (1998). Biaxially Reinforced Multilayer Knit Fabrics for Plastic Reinforcement, *Technical Textiles*, **41**(6): 202–204.

58. Anand, S.C. (1996). Warp Knitted Structures in Composites, In: *Proceedings of Seventh European Conference on Composite Materials*, London UK, **2**: 407–413.

59. Du, Guang-Wu and Ko, Frank (1996). Analysis of Multiaxial Warp-knit Preforms for Composite Reinforcement, *Composites Science and Technology*, **56**(3): 253–260.

60. Ko, F.K., Fang, P. and Pastore, C. (1985). Multilayer Multidirectional Warp Knit Fabrics for Industrial Applications, *Journal of Industrial Fabrics*, **4**: 106–113.

61. Franzke, G., Offermann, P., Bischoff, T. and Wulfhorst, B. (1997). Multi-axial Warp Knitted Layers a Textile for Reinforcing Concrete, In: *Proceedings of 11th ICCM*, 14–18th July, Gold Coast, Australia, pp. 870–880.

62. Dexter, H.B. and Hasko, G.H. (1996). Mechanical Properties and Damage Tolerance of Multiaxial Warp-knit Composites, *Composite Science and Technology*, **56**(3): 367–380.

63. Marvin Dow B. and Benson Dexter H. (1997). Development of Stitched, Braided and woven Composite Structures, NASA/TP-97–206234 (Web based), USA.

64. Smith, P.J., Wilson, R.D. and Gibbins, M.N. (1985). Damage Tolerant Wing Panels for Transport Aircraft, NASA CR-951 (Web based), USA.

65. Wagener, G. (1993). Stitch-bonded Non-crimp Products – New Possibilities for the Reinforcement of Composites, In: *Proceedings of Internationale Techtextil Symposium*, Vol. 3(2), pp. 1–7.

66. Bini, T.B., Ramakrishna, S., Ming Huang, Zheng and Lim, T.C. (2001). Structure-tensile Property Relationship of Knitted Fabric Composites *Polymer Composites*, **22**(1): 11–21.

67. Hong, H., De Araujo, M.D., Fangueiro, R. and Ciobanu, O. (2002). Theoretical Analysis of Load-extension Properties of Plain Weft Knits made from High Performance Yarns for Composite Reinforcement, *Textile Research Journal*, **72**(11): 991–995.

68. Shahnan, W.J. and Postle, R. (1974). A Theoretical Analysis of the Tensile Properties of Plain Knitted Fabrics, Part 1: The Load-extension Curve for Fabric Extension Parallel to the Courses, *Textile Research Journal*, **65**: T200–209.

69. Cook, D.L. and Grosberg, P. (1961). The Load-extension Properties of Warp Knitted Fabrics, *Textile Research Journal*, **3**: 636–643.

70. Gommers, B., Verpoest, I. and Van Houtte, P. (1998), Analysis of Knitted Fabric Reinforced Composites: Part I. Fiber Distribution, *Composites*, **29**: 1579–1588.

71. Luo, Yiwen and Verpoest, Ignaas (1999). Compressibility and Relaxation of a New Sandwich Textile Preform for Liquid Composite Molding, *Polymer Composites*, **20**(2): 179–191.

72. Khondker, O.A., Leong, K.H. and Herszberg, I. (2001). An Investigation of the Structure-property Relationship of Knitted Composites, *Journal of Composite Materials*, **35**(6): 489–508.

73. Khondker, O.A., Leong, K.H., Herszberg, I. and Hamada, H. (2004). Impact and Compression-after-impact Performance of Weft-knitted Glass Textile Composites, *Composites: Part A*, **35**: 145–157.

74. Bannister, M. and Herszberg, I. (1995). The Manufacture and Analysis of Composite Structures from Knitted Preforms, In: *Proceedings of 4th International Conference on Automated Composites*, 6–7 Sept., Vol. 2, Institute of Materials, Nottingham, UK, pp. 397–404.

75. de Araújo, M., Hong, H. and Fangueiro, R. (1996). The Production of Shaped Reinforcing Fabrics by Knitting to Shape, TECNITEX Conference, 20–23 November 1996, Turin, Itália.

76. Hu, Jinlian and Jiang, Yaming (2002). Modeling Formability of Multiaxial Warp Knitted Fabrics on a Hemisphere, *Composites Part A*, **33**: 725–734.

77. de Haan, J., Kameo, K., Nakai, A., Fugita, A., Mayer, J., Wintermantel, E. and Hamada, H. (1997). Notched Strength of Knitted Composites, In: *Proceedings of 11th ICCM*, 14–18th July, Vol. 5, Gold Coast, Australia, pp. 219–226.

78. Herszberg, I., Falzon, P.J., Leong, K.H. and Bannister, M.K. (1996). Bearing Strength of Glass/epoxy Composites Manufactured from Weft Knitted E-glass Fabric, In: *Proceedings of First Australian Congress on Applied Mechanics*, 21–23 Feb., The Institute of Engineers, Melbourne, Australia, pp. 279–284.

79. Savci, S., Curiskis, J.I. and Pailthorpe, M.T. (2000). A Study of the Deformation of Weft-knit Preforms for Advanced Composite Structures Part 1: Dry Preform Properties, *Composites Science and Technology*, **60**(10): 1931–1942.

80. Postle, R. (2002). Structural Mechanics of Knitted Fabrics for Apparel and Composite Materials, *International Journal of Clothing Science and Technology*, **14**(3–4): 257–268.

81. Manson, J.A.E., Rozant, O. and Bourban, P.E. (2000). Drapability of Dry Textile Fabrics for Stampable Thermoplastic Performs, *Composites Part A: Applied Science and Manufacturing*, **31A**(11): 1167–1177.

82. Leong, K.H., Nguyen, M. and Herszberg, I. (1999). The Effects of Deforming Knitted Glass Fabrics on the Basic Composite Mechanical Properties, *Journal of Materials Science*, **34**(1): 2377–2387.

83. Ferland, Pierre, Guittard, Dominique and Ois Trochu, Franc (1996). Concurrent Methods for Permeability Measurements in Resin Transfer Molding, *Polymer Composites*, **17**(1): 149–153.

84. Um, Moon-Kwang and Lee, Sang-Kwan (1999). A Study of Determination of In-plane Permeability of Fiber Preforms, *Polymer Composites*, **20**(6): 771–776.

85. Kim, Sun K., Opperer, Jeremy G., Kim, Dae-Hwan and Daniel, Isaac M. (2003). Determination of In-plane Permeability of Fiber Preforms by the Gas Flow Method using Pressure Measurements, *Polymer Composites*, **24**(1): 34–41.

86. Arendts, F.J. and Drechsler, K. (1991). MB6-Z-0356-RUB=OTN-033059, In: *Proceedings of 3rd International Symposium, Advanced Composites in Emerging Technologies*, 20–24th Aug., University of Patras, Greece, pp. 22–26.

87. Niedermeier, M. and Horsting, K. (1996). Innovative Composite Design Rail Vehicles with Multiaxial Layer Reinforcement Fabrics, In: *Proceedings of Texcomp-3*, Vol. 22(1), Aachen, Germany.

88. Janicka, Jolanta, Kozminska, Romualda and Majewska, Miroslawa (2003). Net-shape Knitted Fabrics as Carrying Elements in Technical Composite Products, *Autex Research Journal*, 3(3): 29–35.

89. Peled, A. and Bentur, A. (2003). Fabric Structure and its Reinforcing Efficiency in Textile Reinforced Cement Composites, *Composites: Part A*, 34: 107–118.

90. Rudd, C.D., Long, A.C., Kendall, K.N. and Mangin, C.G.E. (1997). *Liquid Moulding Technologies*, Woodhead Publishing Limited, Cambridge, UK.

91. Gibbon, J. (1994). Knitting in the Third Dimension, *Textile Horizons*, 14(6): 22–25.

92. Ramani, Karthik and Dai, Heming (2002). Design and Process for Preformed Woven, Knitted and Braided Thermoplastic Composite Arrester, *Composite Materials*, 36(20): 2357–2372.

93. Sheffer, E. and Dias, T. (1998). Knitting Novel 3-D Solid Structures with Multiple Needle Bars, In: *Proceedings of UMIST Textile Conferences-Textile Engineering for Performance*, Manchester, UK.

94. Ramakrishna, S., Ramaswamy, S., Toeh, S.H., Hestings, G.W. and Tan, C.T. (1996). Application of Textile and Textile Composite Concepts for Biomaterials Development, In: *Proceedings of Texcomp-3*, Vol. 27(1), Aachen, Germany.

95. Ming Huang, Zheng and Ramakrishna, S. (1999). Development of Knitted Fabric Reinforced Composite Material for Prosthetic Application, *Advanced Composites Letters*, 8(6): 289–294.

96. Cheng, K.B., Ramakrishna, S. and Lee, K.C. (2001). Electrostatic Discharge Properties of Knitted Copper Wire/Glass Fiber Fabric Reinforced Polypropylene Composites, *Polymer Composites*, 22(2): 185–196.
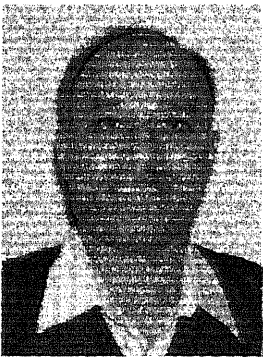
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