

A study of the deformation of weft-knit preforms for advanced composite structures

Part 1: Dry preform properties

S. Savci*, J.I. Curiskis, M.T. Pailthorpe

Department of Textile Technology, School of Material Science and Engineering, University of New South Wales, Sydney 2052, Australia

Received 15 January 1999; received in revised form 1 November 1999; accepted 21 March 2000

Abstract

A weft-knit preform has the potential for its mechanical properties to be tailored, by virtue of the 3-D path of the yarns, in a variety of knitted constructions. The exceptional formability properties (i.e. the ability of a textile preform structure to conform to a 3-D shape) that weft-knit preforms have enable the fabrication of 3-D composite structures by means of resin transfer moulding (RTM). This paper is part one of a two-part series, in which the deformation of weft-knit preforms by the use of a modified California bearing-ratio (CBR) test method is examined. This paper reports the relationship between the physical, mechanical and simulated formability properties of weft-knit glass-fibre preforms. 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 piqué and full cardigan. The results in this section indicate that irrespective of structure, the loop length and tensile properties determine the simulated formability of weft-knit preforms. The second paper provides a composite case study for the formability of weft-knit reinforced composites. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: A. Fabric/textiles; A. Glass fibres; B. Mechanical properties; C. Deformation; E. Knitting

1. Introduction

To the authors' knowledge, not many studies have been reported in the literature on weft-knit dry preform properties relating to advanced composite structures. Hence, studies from the textile industry (i.e. with traditional textile fibres such as wool and cotton) will mainly be reviewed here. These studies may not be entirely relevant because the composite preform material (i.e. high-performance fibres such as glass and carbon) does effect the mechanical properties.

Studies on biaxial loading of plain-knit structures suggest that the deformation is due to yarns passing over one another and is limited by the jamming of yarns at crossing points [1]. Geometric models were later proposed to represent the deformation of plain-knit fabrics under biaxial loading [2]. The trend, however, in the 1970s was to analyze the physical properties of specific weft-knit structures with respect to machine variables and geometric

parameters. Examples include the effect of run-in ratio on Punto-di-Roma and on Swiss and French double Pique structures [3]. Further studies, specifically on extensibility and recovery [4], and compressibility, permeability, extensibility/recovery and bending [5], with a variety of weft-knit double-jersey structures were also pursued. In fact, studies relating the bending stiffness and extension stiffness of the component fabrics to the final 'composite' fabric were also carried out [6]: the composite fabric is used in apparel applications rather than engineering.

The only other relevant work on weft-knit preforms is a mechanical model for predicting the deformation behaviour and mechanical properties of weft-knit fabrics based on a plain stitch, by the use of a 2-D hexagonal representation with slippage effect [7]. Although this model claims to have verified the model with experimental tensile data, it is unlikely that the strain behaviour of a 3-D structure, (i.e. plain knit being analyzed) can be accurately predicted using a 2-D model. Although the third dimension may be neglected for some mechanical behaviour such as bending stiffness, it is not the case for

*E-mail address: sule_savci@yahoo.com.au (S. Savci).

the internal strain fields which determine the location between the onset of non-linear behaviour, including crack initiation and propagation. This has been demonstrated for individual short-fibre composites by comparing 2-D and 3-D finite-element analyses [8]. In addition, it should be realised that the details of loop structure in the dry preform will be determined by minimum energy considerations, including the effects of knitting relaxation, subsequent handling and composite fabrication.

2. Principles of weft knitting

Weft knitting, by definition, is a method of making a fabric by normal knitting means in which the loops made from each weft thread are formed substantially across the width of the fabric [9]. Furthermore, weft knitting is characterized by the fact that each yarn is fed at right angles to the direction in which the fabric is produced [9]. The principles of weft knitting are explained in greater detail elsewhere [10,11]. In addition to the basic stitch types and weft knitting notation, there is also a terminology used to characterize weft-knit structures. The fundamental terms used to characterize weft-knit structures are shown in Table 1.

Investigations on the dimensional stability of plain weft-knit fabrics showed that the textile tends towards a form of lowest energy state known as the relaxation state [12]. Subsequent studies revealed that the process of reaching this relaxation state varied for various fibre types but they all showed that the geometry of the knitted fabric in the relaxed state depends on the loop length [13,14]. This revelation also implies that, under states other than the fully relaxed one, the forces applied during the knitting process will tend to influence

fabric geometry. The generalization that fabric geometry depends on the existence of various relaxation states of the fabric has been shown to be primarily true for wool and to a lesser degree for synthetic fibres. Munden describes the stable state of a fabric (fully relaxed state) as being one of minimum energy such that if the dimensions of the stable state are changed from the stable condition, the fabric will, of its own accord, return to the same stable dimensions [12]. Studies in the geometry of weft-knit wool fabrics have resulted in numerous methods for reaching fully relaxed states, such as washing, conditioning and drying for specified periods of time. The consequences of these studies were 3 relaxation states, namely wet-relaxed, dry-relaxed and finished relaxed. More specifically, relaxation of the textile enables us to calculate a constant value, which relates the loop length of the knit to either, its course density, wale density or stitch density. Table 2 below gives an example of fabric geometry constants for various finished stable states [15] derived from Munden's equations [12] for plain knit worsted fabrics. Eq. (1) illustrates these relationships. The geometry of knitted fabrics is reviewed in greater detail by Hearle et al. [16].

Eq. (1): Munden's equations relating stitch density to loop length.

$$\begin{aligned}
 R = \text{shape factor} &= c/w \text{ (constant aspect ratio of unit cell)} \\
 \text{course density} &= k_c / \text{loop length} \\
 \text{wale density} &= k_w / \text{loop length} \\
 \text{stitch density} &= k_s / \text{loop length squared}
 \end{aligned}
 \tag{1}$$

Past work on the geometry of weft-knit fabrics has both established relationships between the fabric's dimensions and energy states plus providing an understanding of the 3-dimensional nature of the loops. The

Table 1
Fundamental terms of weft-knit structures

Term	Abbreviation	Definition
Course	c	A row of loops either across the width of a flat fabric or around the circumference of a circular fabric
Wale	w	A column of loops along the length of a fabric
Loop length	L (mm)	The length of yarn to form one complete knitted stitch
Average loop length	L_{av} (mm)	Total length of yarn to form a repeat divided by the number of stitches in the repeat structure
Course density	c/cm	The number of visible loops per unit length measured along a wale
Wale density	w/cm	The number of visible loops per unit length measured along a course
Areal density	g/m^2	Mass of fabric in grams per area in square metres
Tightness factor	K	$\sqrt{\text{Tex}}$ per average loop length (it also indicates the extent to which the area of the fabric is covered by yarn)
Run-in ratio	$L_1:L_2:\dots:L_n$	Ratio of loop lengths in a structural repeat, where n is the number of different courses
Tex	T	Linear density of yarn in grams/1000 m

Table 2
An example of weft-knit geometry constants (worsted yarn) [40]

Relaxation state	k_s (Tex mm ⁻²)	k_c (Tex ^{1/2} mm ⁻¹)	k_w (Tex ^{1/2} mm ⁻¹)	$R = k_c/k_w$
Dry relaxed	1900	50	38	1.31
Wet relaxed	2160	53	41	1.29
Finished relaxed	2360	56	42.2	1.32

findings relating to the dimensional stability of weft-knit fabrics instigated the development of computer software programs to enable the prediction of shrinkage and dimensional properties of textiles such as knitted cotton fabrics [17]. The software is known as Starfish (i.e. start as you mean to finish) which means that the requirements of the final product are specified so that a specification of its manufacturing settings may be determined. The system is a database of various knit structures, machine types and yarn types with various finishing routes and was designed to provide a systematic approach to the manufacture of cotton knitted fabrics. This is a particularly useful tool, because it inevitably translates to time and money savings. Various theoretical models have also been developed to depict the configuration and proportions of plain weft-knit fabrics [e.g. 18,19]. However, there has been little work undertaken on the geometry of weft knits with respect to composites.

3. Preform deformation

The technology involved in shaping via integral knitting has been explained elsewhere [11]. The other method of shaping is either by stretching or simply placing a flat preform over a moulded shape, thus forcing it to deform to the shape of the mould. Shaping in this fashion is known as deep drawing and is often accompanied by a matching mould, which confines the preform between the two moulds.

There is one study that analyses the deformation of weft-knit reinforced composites [20]. It also proceeds to analyze the parameters that influence the composite's mechanical properties. Studies describing various application areas for shaping with weft-knit preforms in this manner are growing. For example, weft-knit preforms are ideal for bone plate implants because their extensibility may be utilized to adapt to the stiffness of the underlying bone and the preform also enables the formation of holes without machining, hence the mechanical properties around these areas remain unaffected [21]. Another application area that has received attention from deep drawn weft-knit preforms is automotive structures [22]. An attempt was made to analyze the preform geometry against various degrees of stretching. However, the study was carried out using copper as a

binding filament against a carbon preform to provide the analysis [23] and thus it is not entirely clear whether the differences in mechanical properties between copper and carbon will interfere with the deformation behaviour of the carbon structure. Another area of interest for the use of deep drawn weft-knit preforms is in the aerospace industry [24]. This paper demonstrates the deformation of weft-knit glass fabrics and proceeds to analyse the deformation with respect to the dimensions and mechanical behaviour of both the milano structure and its component, plain and rib structures.

However, to the authors' knowledge, there have been no other studies carried out on the properties of the dry preform and although there are studies on fabric drape such as in reference [25], they do not relate to moulding in the way that formability does. No formability concepts have been developed for shaping, yet it has been well established that weft knitting is an excellent candidate for forming complex shapes due to its formability properties.

4. Experimental procedure

Selected weft-knit preforms were manufactured using 68×2 Tex glass fibre tows, with silane size from Silenka Yarns, on an 8-gauge (E8) Stoll ANVH/BLM-es knitting machine. The computer controlled rib-jacquard machine used the programming language Sintral [11] enabling needle selection, cam settings and takedown tension setting control. The most important control features include yarn-input tension, fabric takedown tension, cam setting and speed. Various structures were manufactured by manipulating the cam settings. An idealized schematic representation of the full milano structure is given in Fig. 1.

The full milano structure is made up of one course of 1×1 rib and 2 courses of single jersey (one course on the front bed and one course on the back bed in order to give a balanced structure). In this paper, first the results for the full milano structure are reported. The various structures used in the first part of the analysis are shown in Table 3 where 'M' stands for full milano, 'L' is the rib loop length, and 'Lp' is the plain loop length. During the manufacture of the preform, all parameters except the stitch cam settings were kept constant. The machine settings chosen for this investigation were based on the tightest possible structure (M3N) and the remaining preforms were produced at machine setting intervals that enabled statistical difference between the various preforms.

The basic physical properties of textile structures determine their dimensions and hence give an outline of the macro structure. For weft knits, these properties are as follows: thickness, areal density, loop length, run-in ratio, course density, wale density and tightness factor. The loop length was measured with a hand-held yarn tension and length metre during manufacture of the

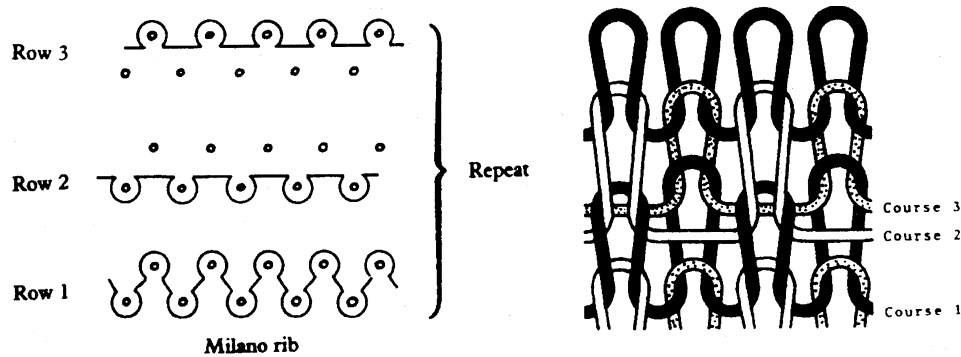


Fig. 1. Full-milano, 1x1 rib and single jersey structures, respectively.

structure. The other method of measuring the loop length is to cut a specific number of courses out of the structure and unravel the yarn, measure its length and divide it by the number of stitches to derive the loop length. The latter method was used due to the better accuracy (± 0.1 mm per stitch) which it provided.

There is no standard test method for evaluating a preform's formability. But there is the California bearing-ratio (CBR) plunger method for determining the burst strength of geotextiles as outlined in AS3706.4 [26]. In this test, a cylindrical plunger is forced through the centre of a circular specimen that is gripped around its entire circumference by clamps in a loading frame. The test method was modified to include a spherical plunger in order to assess the affect of a different shape/surface area on the simulated formability properties. The apparatus used in this test consists of clamping rings that are grooved and toothed concentrically to prevent slippage of the specimen. Matching bolt holes locate teeth and grooves accurately. The rings are clamped by tightening the bolts. A schematic illustration of the CBR test method is shown in Fig. 2 and the plungers used are shown in Fig. 3. The plunger is normally lowered until it penetrates through the preform specimen. However, this method was used to a maximum displacement of 50 mm only, rather than to specimen failure (i.e. burst strength)

to evaluate the simulated formability of the preform and all data reported here relate to the final displacement level. The reactive force at specified plunger displacement intervals and the energy yielded for those displacements were measured and utilised as the simulated formability data. The Instron 1122 was used in the compression mode, together with a plunger displacement speed of 20 mm/min. It should be noted that although the CBR test method is not an exact simulation of the deformation that takes place during RTM, in light of the absence of any other technique being available, it was chosen as a starting basis for assessing formability.

In textiles, there is a measurement system available called KESF, which is used for assessing the structure's low stress mechanical and surface properties. The KESF instrumentation allows a total of 5 basic properties to be described, but only the following four were used in this research: in-plane tension, in-plane shear, transverse compression, and out-of-plane bending. The instruments are designed to take measurements at low stress levels whilst providing data on a wide range of parameters including deformation and recovery for each mechanical property obtained.

A detailed operating procedure for the KESF instrumentation is given elsewhere [27], but the standard parameters defined from the tensile curve (Fig. 4) are

Table 3
Mean physical properties of full milano preforms

Fabric	Areal density (g/sq m)	Rib loop length (mm)	Plain loop length (mm)	Course density (c/cm)	Wale density (w/cm)
M3N	743	6.36	5.94	8.9	4.8
M32	672	6.89	5.73	8.6	4.3
M33	661	7.80	5.53	8.9	3.9
M34	574	8.79	5.40	8.2	3.4
M71	693	6.14	7.49	7.8	4.6
M72	595	6.76	7.18	7.5	4.1
M73	560	7.51	7.10	7.5	3.6
M74	557	8.08	6.41	7.8	3.4
M9	447	8.80	8.73	6.5	2.8
M93	513	7.51	8.65	6.7	3.6

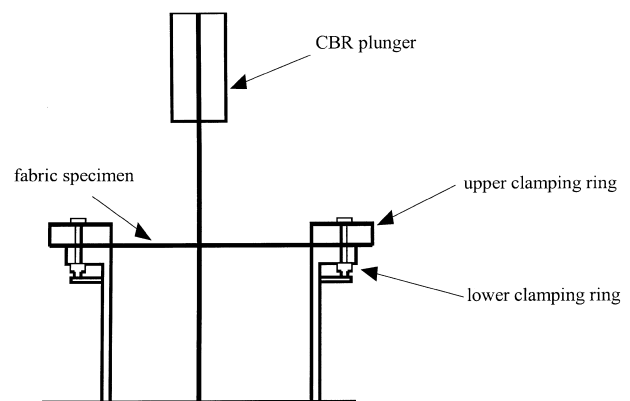


Fig. 2. General schematic arrangement of the CBR test method.

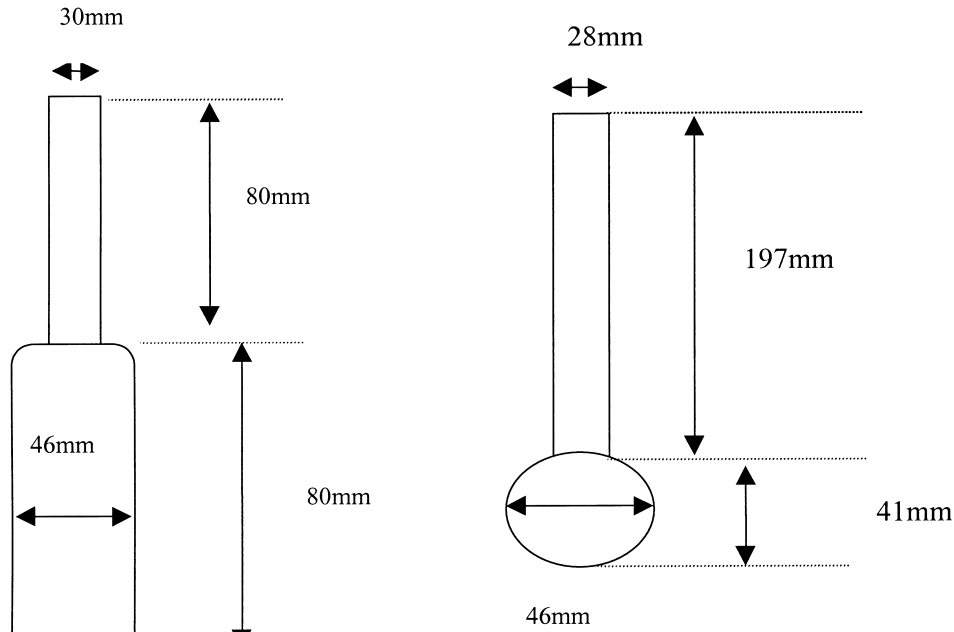


Fig. 3. Metal plunger and ceramic plunger, respectively, used in the CBR test method.

given in Table 4. Since the tensile properties are the only KESF properties reported in this paper, a brief description of the test method is also given. This test method requires the testing of 10 specimens in the wale and course directions in specimen sizes of 20×20 cm. Each specimen is extended to a maximum load of 500 gf/cm, which converts to 490 N/m in SI units. The load and corresponding fabric extension were recorded simultaneously in one extension and recovery curve. The preform extensibility and tensile resilience were also calculated. The principle of the tensile instrument is to measure tensile resistance by extending the fabric in the relevant principal direction (viz. course and wale).

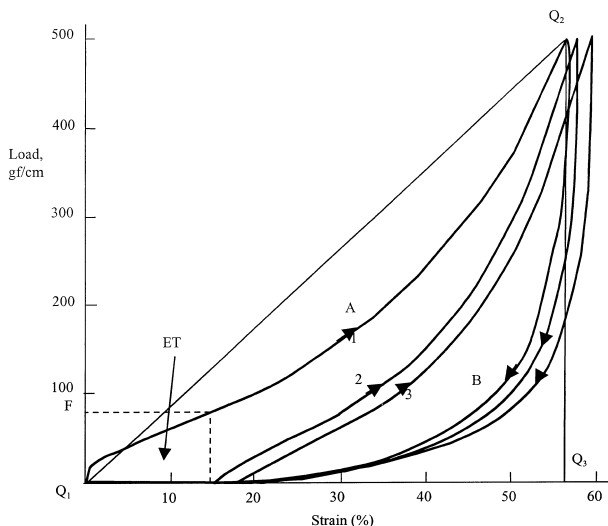


Fig. 4. Typical KESF tensile deformation-recovery curve.

Assessment of the mechanical properties could not be performed directly using linear regression since the data could not be matched during the experimentation. The nature of the fabric inevitably lead to permanent deformation after undergoing mechanical manipulation (i.e. destructive tests) and consequently the observations were not matched. Instead, the means of the variables were used to find relationships between the mechanical and simulated formability properties. Initially, regressions on the mean data were performed and used together with graphical representations in order to eliminate any properties that had no relationship with the mechanical properties. Secondly, properties of borderline significance were compared to regressions without the inclusion of the mechanical property in question and rejected according to its contribution to the adjusted R^2 .

The final part of the study was to determine the effect that the knit structure had on the preform's simulated formability. Fig. 5 shows the loop sequence diagrams for the different knit structures used in studying the effect of knit structure on simulated formability. The first structure includes the full milano, the second is alternating half milano which consists of one course of 1×1 rib and one course of single jersey on one bed plus a repetition of this sequence with the single jersey on the opposing bed. The full cardigan structure is made up of knit stitches on the front bed and tuck stitches on the back bed for one course, plus another course of knit stitches on the back bed and tuck stitches on the front bed. The French double pique structure consists of a four course loop sequence. The first course consists of a knit stitch and float stitch on the back bed (half gauge single jersey), and the second course has a 2×1 rib (knit

Table 4
Standard parameters defined in KESF tensile testing

Variable	Property	Definition	Units
LT	Linearity of load extension curve	WT/area $Q_1 Q_2 Q_3$	%
WT	Energy in extending fabric to 500 gf/cm width	area $Q_1 A Q_2 Q_3$	J/m ²
RT	Tensile resilience	area $Q_1 B Q_2 Q_3$ / WT	%
EMT	Fabric extension at 500 gf/cm width	Q_3	%
FT	Load at 15% fabric extension	FT	N/m
ET	Energy at 15% fabric extension	ET	J/m

front, knit back and knit front). The third course has a miss stitch and knit stitch also on the back bed, plus another 2×1 rib (knit 2 on the front and knit one on the back) for the fourth course. These knit structures were all produced using the same machine settings and their mean physical properties are listed in Table 5, where M represents the full milano, F denotes French double pique, H denotes the half milano and C represents the full cardigan structure.

5. Interaction between physical and simulated formability properties

The measured loop lengths were chosen to represent the physical properties. Loop lengths are commonly used to define a knitted structure's dimensions and other physical properties may theoretically be derived from them. Therefore, the measured loops were used to represent the physical properties. The aim of this work was to determine if there was a relationship between

loop length and simulated formability as well as mechanical and simulated formability properties.

The interaction was first investigated in relation to the aluminum cylinder shaped surface followed by the ceramic spherical shaped surface plunger. Initially individual regressions of both loop lengths with each simulated formability result were analysed. A summary of the regression between simulated formability and loop length is shown in Table 6. FCL refers to the measured load and FCE refers to the measured energy to deform the preform using the cylindrical plunger. FSL refers to the measured load and FSE refers to the measured energy to deform the preform using the spherical plunger.

Fig. 6 is the typical stress/displacement curve using the CBR test method. The results indicate that the preform undergoes an exponential increase in the required force (simulated formability) as the plunger progressively penetrates the preform. Figs. 7 and 8 indicate the interaction between simulated formability and the physical properties for both the cylindrical and the spherical plungers.

These results show that an increase in the plain loop length results in a smaller force and less energy to deform the fabrics. This means that the simulated formability of the full milano preform structures improves or, in other words, the ease with which a preform deforms to a 3-D shape improves with increasing plain loop length. However, the results also showed that there was not a significantly high correlation between the rib loop length and simulated formability. Therefore, the results indicate that the plain loop length is the constricting parameter in determining the simulated formability of the preforms and consequently can be used to accurately predict formability for shaping applications. The yarn path of the plain loop length in the preform is

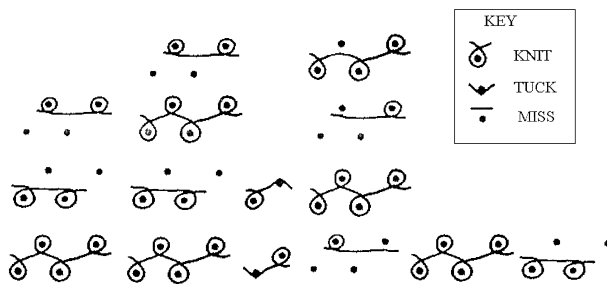


Fig. 5. Full-milano, alternating half-milano, full-cardigan, French double pique, 1×1 rib and single jersey structures, respectively.

Table 5
Mean physical properties of different knit structures

	Areal density (g/sq m)	Rib loop length (mm)	Plain loop length (mm)	Course density (c/cm)	Wale density (w/cm)
M73	560	7.52	7.10	7.5	3.6
F73	704	7.20	4.68	9.0	3.7
H73	539	7.53	6.25	5.2	3.5
C73	739	—	7.05	6.0	3.0

Table 6
Summaries of regressions for formability with the plain loop length as the independent variable

Property	R ²
FCE5	0.77
FCL5	0.75
FSE5	0.70
FSL5	0.79

confined to a smaller area of space since it is only knitted on one needle bed per course. On the other hand the rib loop length occupies two knitting beds per course, and it is this architecture that provides rib structures with more extensibility. Hence, it is reasonable to conclude that the plain stitches, of the two stitch types, would impose more restrictions on deformation during shaping.

The results of the simulated formability for the spherical plunger also indicated that the plain loop length was a better predictor than the rib loop length component with similar trends to those found in the previous tests. But the simulated formability for the spherical plunger was almost half the simulated formability for the cylindrical plunger. This means that the surface shape and covering of the plunger play a critical role in determining formability. Consequently, the frictional forces developed during deep drawing over a mould (i.e. surface shape/material) will likewise effect the formability of a preform for composite fabrication.

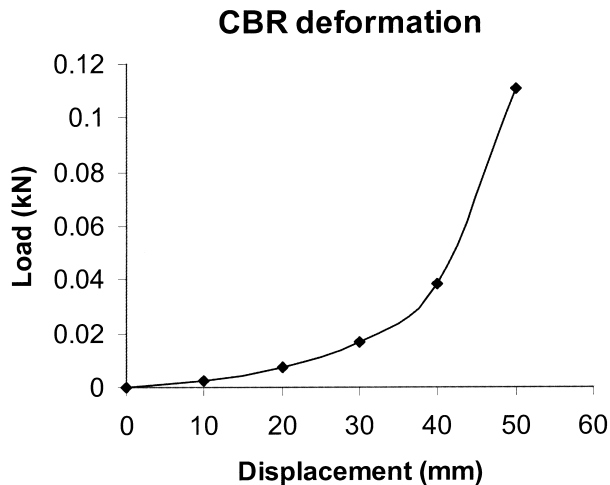


Fig. 6. Typical deformation curve for a weft-knit subjected to CBR test method.

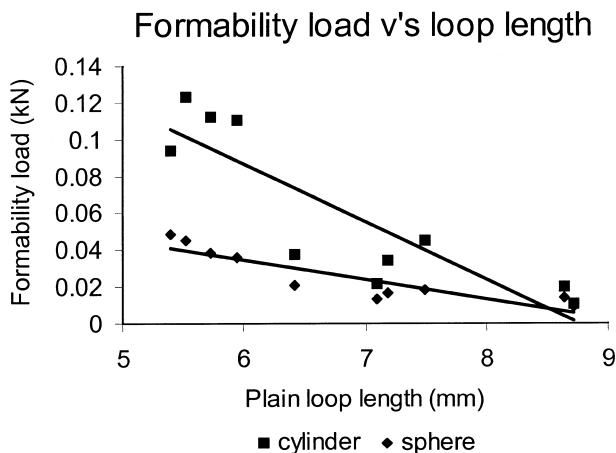


Fig. 7. Relationship between physical properties and formability load.

6. Results of the interaction between mechanical and simulated formability properties

In addition to the standard KESF parameters, 4 other variables in the tensile mode were introduced in order to compare the simulated formability to a comparable level of extension in the tensile test. This was achieved by a single calculation to determine an approximate level of extension during the simulated formability test method. The internal diameters of the fabric in the clamps of the CBR test method were 150 mm, thus giving a radial of 75 mm (Fig. 9). The simulated formability analysis is based on the 50 mm displacement; hence the hypotenuse of these right-angled triangles can simply be used to determine the level of extension.

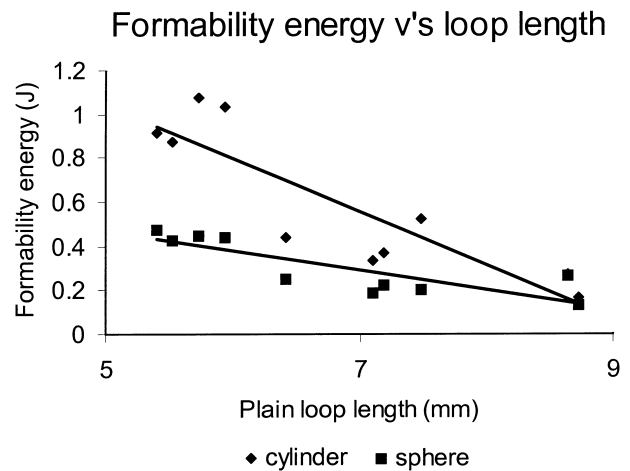


Fig. 8. Relationship between the physical properties and formability energy.

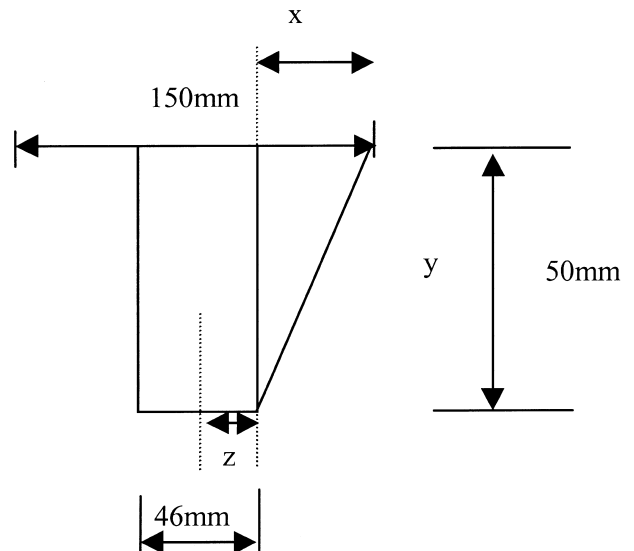


Fig. 9. Calculation of extension for the CBR test method.

Eq. (2): Extension with friction:

$$\text{where } A_1 = \frac{\sqrt{(x^2 + y^2)} - x}{x} X = 38.7\%$$

$$\% \text{ extension} = \frac{(\text{final length} - \text{initial length})}{\text{initial length}} \times 100\%$$

$$= \frac{[\sqrt{(52^2 + 50^2)} - 52]}{52} \times 100$$

$$= 38.7\%$$
(2)

Eq. (3): Extension without friction:

$$\text{where } A_2 = \frac{\sqrt{(x^2 + y^2)} + z - [x + z]}{x + z} \times 100\%$$

$$\% \text{ extension} = \frac{(\text{final length} - \text{initial length})}{\text{initial length}} \times 100\%$$

$$= \frac{[\sqrt{(52^2 + 50^2)} + 23 - [52 + 23]]}{[52 + 23]} \times 100\%$$

$$= 26.9\%$$
(3)

Extension with and without the inclusion of friction was calculated. The results of the calculations revealed that there was a 38.7% [Eq. (2)] and 26.9% [Eq. (3)] fabric extension during the simulated formability test method based on the possibility of no slippage and also with slippage, respectively. The level of extension used as the base for determining the force and energy variables in the KESF tensile test does not necessarily need to correspond to these extension levels. However, it is important that the designated extension level be achievable by all preforms and secondly the ratio of the force:extension be approximately constant for each curve. Preform F73 for instance indicated a maximum extension level of 24% hence the designated extension level needed to be less than 24%. It was also found that the majority of the tests exhibited linearity at the 15% level, therefore, the force (FT) and energy (ET) at the 15% strain level was used for the analysis.

The results indicated that there was not a sufficient correlation between simulated formability and linearity of compression, compressibility, and fabric extensibility for the course and wale directions. The findings show that there is a very high correlation between the tensile force in the course direction required to extend the fabric to 15% (FTC) and simulated formability. The results also showed that there was equally a high correlation between the tensile energy in the course direction (ETC) and simulated formability for both plungers. There is also some correlation between simulated formability and shear rigidity as well as simulated formability and bending rigidity. Combinations of the most highly correlated properties are listed in Table 7, in order to

determine which properties significantly contribute to the R^2 value.

The results showed that although shear rigidity and bending rigidity do contribute to the correlation, the tensile properties mentioned above are the better prime predictors based on the inclusion of each KESF parameter in the prediction of the simulated formability parameter (i.e. R^2). The findings also showed that the course direction in these mechanical properties provides a better correlation with simulated formability than the wale direction. Finally, apart from the difference in the magnitude of the simulated formability between the two plunger types, there also appears to be a slight difference in the composition of their mechanical properties. The results indicate that shear plays a more important role in determining the simulated formability using the cylindrical plunger while the spherical plunger inclines towards bending rigidity. More importantly, however, all the evidence indicates that the simulated formability of a preform is governed by the fabric's tensile properties at an equivalent extension level. Furthermore, the high correlation between shear and simulated formability

Table 7

Correlation combinations of top four mechanical properties with formability

R^2	BRIGC SRIGC FTC	BRIGC SRIGC ETC	BRIGC FTC	BRIGC ETC	SRIGC FTC	SRIGC ETC	FTC	ETC
FCE5	0.96	0.94	0.92	0.93	0.95	0.94	0.91	0.92
FCL5	0.96	0.97	0.91	0.94	0.96	0.97	0.91	0.94
FSE5	0.93	0.95	0.93	0.93	0.90	0.93	0.90	0.91
FSL5	0.96	0.96	0.95	0.93	0.96	0.95	0.94	0.92

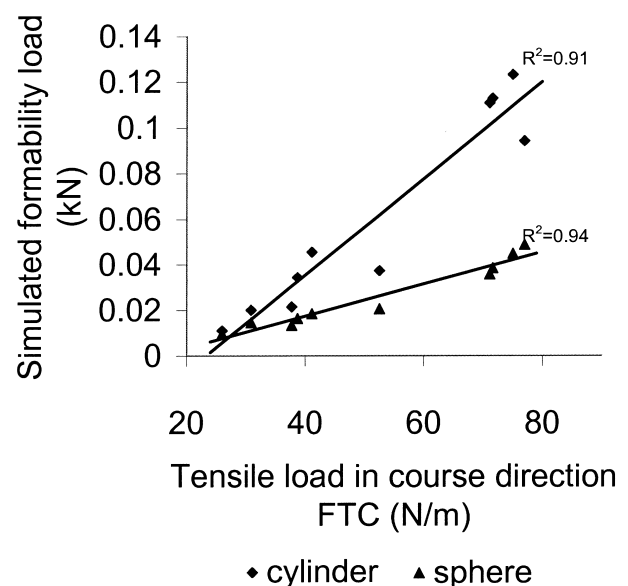


Fig. 10. Relationship between simulated formability load and tensile load.

confirms the relationship between the tensile and simulated formability properties. This is because it is not possible to actually shear a knitted fabric. The actual mode of deformation is more closely related to extension in a diagonal direction.

The results strongly suggest that both the tensile energy and load to extend the fabric to 15% correlate with the simulated formability of the fabric to the equivalent level of extension. The relationships between these specified tensile parameters and simulated formability for the cylindrical and spherical plungers are shown in Figs.

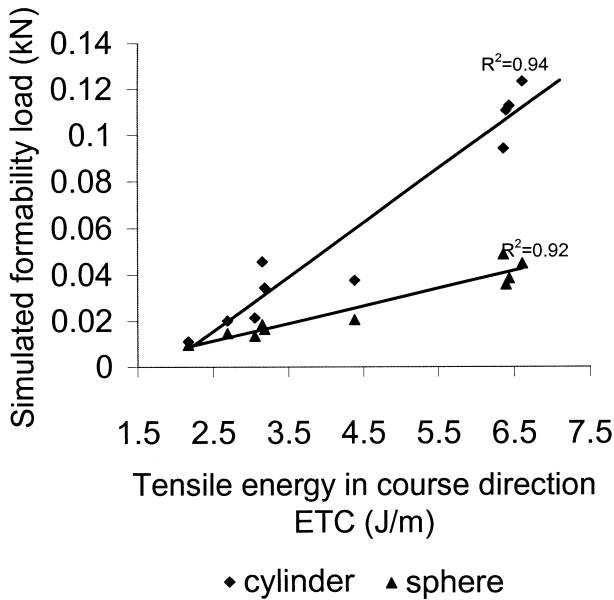


Fig. 11. Relationship between simulated formability load and tensile energy.

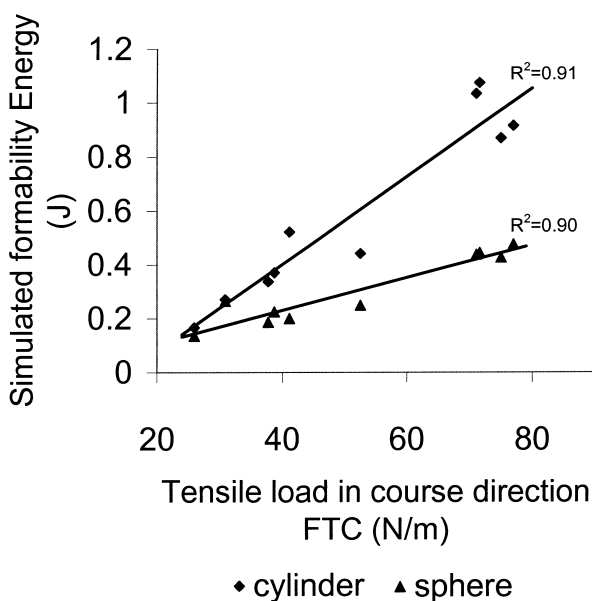


Fig. 12. Relationship between simulated formability energy and tensile load.

10–13. The results show that an increase in the tensile load or energy corresponds to an increase in the simulated formability energy and in the simulated formability load. This means that the larger the force that is required to deform the fabric in the tensile mode, the larger is the required force to deform a fabric during deep drawing. In fact, the findings indicate with a high degree of confidence that the tensile properties alone may be used to predict the simulated formability of a full milano fabric.

The results for the spherical plunger also showed that an increase in the tensile load corresponded to an increase in the simulated formability load or energy. The main difference between the results for the cylinder and the sphere were in the magnitude of the simulated formability properties. The overall results showed that for the structure studied, tension is the best predictor of simulated formability.

7. Effect of knit structure on simulated formability

Summaries of the effect of knit structure on simulated formability results are given in Table 8 where FSL and

Table 8

Mean simulated formability properties of different knit structures

	M73	F73	H73	C73
FCE5 (J)	0.369	4.905	0.428	0.079
FSE5 (J)	0.185	1.226	0.22	0.053
FCL5 (kN)	0.022	0.941	0.033	0.004
FSL5 (kN)	0.01339	0.15099	0.01635	0.0026

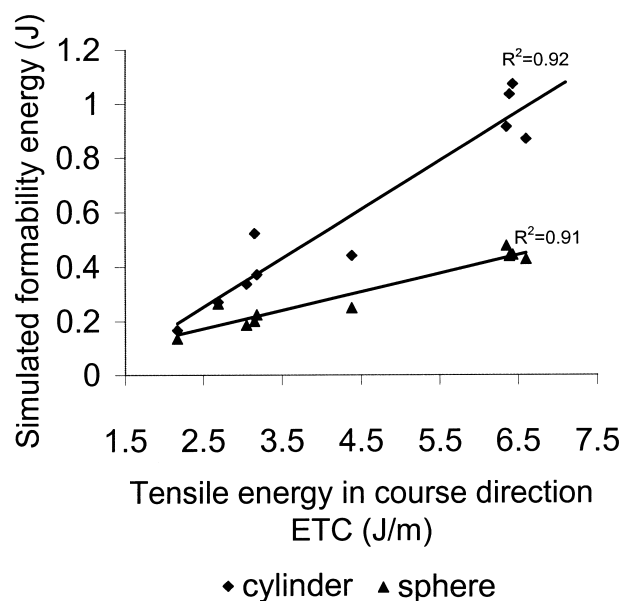


Fig. 13. Relationship between simulated formability energy and tensile energy.

FCL represent the loads to deform the preforms for the spherical and cylindrical plungers, respectively. FSE and FCE represent the energies to deform the preforms for the spherical and cylindrical plungers, respectively.

The simulated formability results for the various knit structures indicate that a larger force is required to deform each fabric to the 50 mm displacement level for the cylindrical cylinder than the spherical plunger. The

knit structure also influences the degree of increase between the two plunger types. All structures indicate a 2:1 ratio while the French double pique indicates a 5:1 ratio decrease in force for the cylindrical to spherical plunger types. Furthermore, the results of the simulated formability rank the full cardigan as the most formable followed by both milano structures, and the French double pique ranks as the least formable.

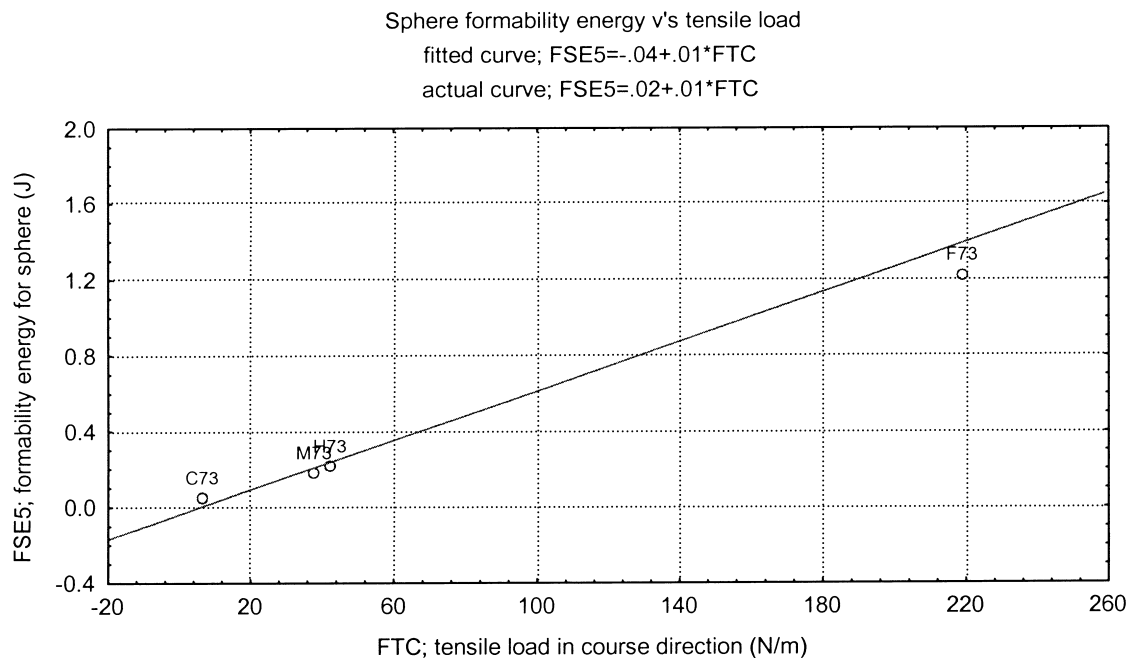


Fig. 14. Compliance of different knit structure to milano relationship for simulated formability energy with tensile load.

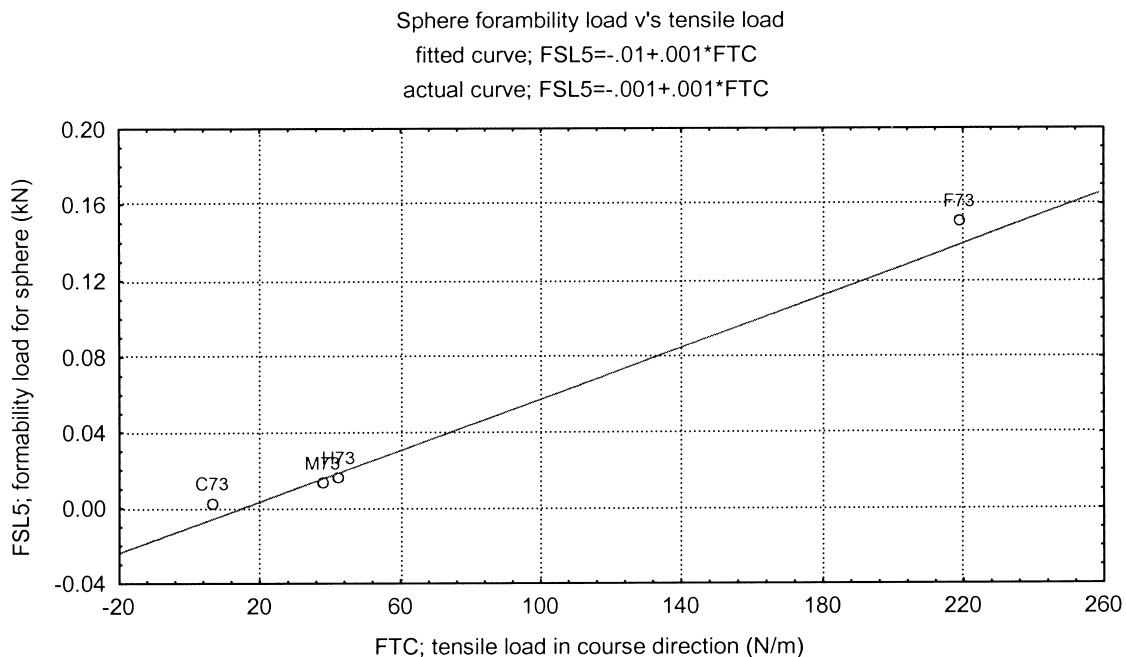


Fig. 15. Compliance of different knit structure to milano relationship for simulated formability load with tensile load.

The full milano structure was investigated in greater detail, thus enabling the development of a relationship between formability and the plain loop length as well as formability and KESF tensile properties. Although there were not as many data on the different knit structures, their respective formability, plain loop length and KESF tensile properties were analysed. Although the actual relationship between formability and plain loop length for the different knit structures was quite different from the full milano results, the results showed that the plain loop length still plays a dominant role in determining the preforms' formability. However, the similarities between the extensive milano investigation and the different knit structures was very evident and hence, have been illustrated in Figs. 14 and 15. The graphs show the mean values of the simulated formability and tensile load for the different knit structures with the relationship found for the milano structure in order to compare the findings of the two relationships. The results for the interaction between formability and tensile properties showed some difference in the coefficient of the y -intercept, but otherwise displayed a similar trend for all structures (i.e. approximately the same slope).

8. Concluding remarks

The simulated formability of the dry preforms was investigated in relation to their physical and mechanical properties. The results for the full milano structure showed that the plain loop length could be used to represent the physical properties enabling a relatively good prediction of simulated formability. The findings also showed that the surface material and shape of the plunger greatly influenced the simulated formability of the preform. The results for the full milano structure showed that the KESF tensile load or energy enabled a good prediction of simulated formability provided that they represent approximately equivalent levels of extension. The findings also showed that the surface material and shape of the plunger greatly influence the simulated formability of the preform. Both findings enabling the prediction of the simulated formability for weft-knitted preforms were confirmed with different knit structures. These results have clear implications for composite fabrication via deep drawing processes and subsequent resin infusion.

Acknowledgements

The senior author would like to thank the Cooperative Research Centre for Advanced Composite Structures (CRC-ACS) for the provision of a post graduate scholarship and for the financing of this research.

References

- [1] MacRory BM, McNamara AB. Kitted fabrics subjected to bi-axial stress — an experimental study. *Textile Research Journal* 1967;37:908–11.
- [2] MacRory BM, McCraith JR, McNamara AB. The bi-axial load extension properties of plain weft-knitted fabrics — a theoretical analysis. *Textile Research Journal* 1975;45:746–60.
- [3] Knapton JJF. Knitting high quality double jersey cloth: parts I–V: Textile Institute and Industry, 1972; February: 39–42, 1972; March: 38–72, 1972; April: 103–106, 1973; December: 345–348, 1974; January: 18–21, 1974; June: 178–181.
- [4] Knapton JJK. The engineering of knitted fabrics for industrial applications. *Proceedings of 61st annual conference of Textile Institute*, 26–34 September 1977.
- [5] Knapton JJF, Lo FWK. Knitting high quality double jersey cloth — Part VII; the influence of structure on some mechanical properties. *Textile Institute and Industry*, 1975, November: 355–358.
- [6] Shishoo R, Klevmar PH, Cednas M, Olofsson B. Multi-layer textile structures: relationship between the properties of a composite and its components. *Textile Research Journal*, 1971; August: 669–679.
- [7] Wu WL, Hamada H, Maekawa ZI. Computer simulation of the deformation of weft-knitted fabrics for composite materials. *Journal of the Textile Institute* 1994;85(2):198–214.
- [8] Curiskis JJ. On the determination of the non-linear longitudinal mechanical behaviour of short-fibre composites by a three-dimensional finite element procedure. *ICCM 3* 1980;1:796–811.
- [9] Tubbs MC, Daniels PN. editors. *Textile Terms and Definitions*, 9th ed. Manchester: Textile Institute, 1991.
- [10] Spencer D. *Knitting Technology*. Pergamon Press: Oxford, 1989.
- [11] Raz S. *Flat knitting: the new generation*. Meisenbach: Bamberg, 1991.
- [12] Munden DL. The geometry and dimensional properties of plain-knit fabrics. *Journal Textile Institute* 1959;50T:448–71.
- [13] Postle R. Dimensional stability of plain-knitted fabrics. *Journal of Textile Institute* 1968;59(2):65–77.
- [14] Knapton JJF, Ahrens FJ, Ingenthron WW, Fong W. The dimensional properties of knitted wool fabrics: part I the plain knitted structure. *Textile Research Journal* 1968;38:999–1012.
- [15] Anon. Recent progress in the geometry of weft-knitted wool fabrics. *Wool Science Review*, 1969; October (37), 3–22.
- [16] Hearle JWS, Grosberg P, Backer S. *Structural mechanics of fibres, yarns and fabrics*. USA: John Wiley and Sons, Vol. 1, 1969.
- [17] Heap SA, Greenwood PF, Leah RD, Eaton JT, Stevens JC, Keher P. Prediction of finished weight and shrinkage of cotton knits — the starfish project, parts I and II: Review. *Textile Research Journal*. 1983; February: 109–119, 1985; April: 211–222.
- [18] Hepworth RB. *Mechanics of an idealized yarn in the configuration of plain weft-knitting*. PhD thesis, Leeds, 1971.
- [19] DeJong S. *A study of fabric mechanics using energy methods of analysis*. PhD. thesis, UNSW, 1976.
- [20] Wu WL, Hamada H, Kotaki M, Maekawa Z. Design of knitted fabric reinforced composites, *Journal of Reinforced Plastics and Composites*, 1995; 14 (August): 786–798.
- [21] Ruffieux K, Hintermann M, Mayer J, Koch B, Wintermantel E. Enhanced local carbon fibre knitting reinforcement of mechanical adapted bone plates. Concept of a new implant, *Textiles and Composites*, 1992; June: 326–331.
- [22] Mayer J, Ha SW, Ruffieux K, Tognin R, Kock B, Wintermantel E. Knitted Fibre Reinforced Composites. *Automotive Engineering*, 1994; August: 21–24.
- [23] Mayer J, Luscher P, Wintermantel E. Knitted carbon fibre reinforced thermoplastics: structural characterization with image analysis. *Textiles and composites*, 1992; June: 315–320.

- [24] Savci S, Curiskis JI. Weft-knitted glass fibre preforms for composite materials, ICCM 11, Queensland, 14–18 July, 1997;5:338–348.
- [25] Chen B, Govindaraj M. A parametric study of fabric drape. *Textile Research Journal*, 1996; 66 (January): 17–24.
- [26] AS3706.4, Method 4: determination of burst strength — California Bearing Ratio Plunger Method, Geotextiles — Methods of test. Standards Australia, 1990.
- [27] Kato Tekko Co. Ltd., KES-FB-1, KES-FB-2, and KES-FB-3: Manual for pure bending tester. Tensile and Shear Tester, Compression Tester, Kyoto, 1991.