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Development of 3D Knitted Fabrics for Advanced Composite Materials

Luminita Ciobanu, Ph.D., Eng.
„Gheorghe Asachi" Technical University of Iasi
Romania

1. Introduction

Generally, a composite material is made of distinct materials, that together act in a different way than when considered separately. There are a lot of examples of composite materials, both natural and synthetic, from the human body, to buildings, airplanes and so on.
Most comprehensive definition of the composite materials that characterises their nature is given by P. Mallick. According to Mallick (1997), a composite is a combination of two or more chemically different materials, with an interface between them. The constituent materials maintain their identity in the composite material (at least at macroscopic level), but their combination gives the system properties and characteristics different from those of each component. One material is called matrix and is defined as the continuous phase. The other element is called reinforcement and is added to the matrix in order to improve or modify its properties. The reinforcement represents the discontinuous phase, distributed evenly in the matrix volume.
There are several options for reinforcement and matrix, as illustrated in Fig.1, that are taken into consideration based on the mechanical requirements specific to the application.

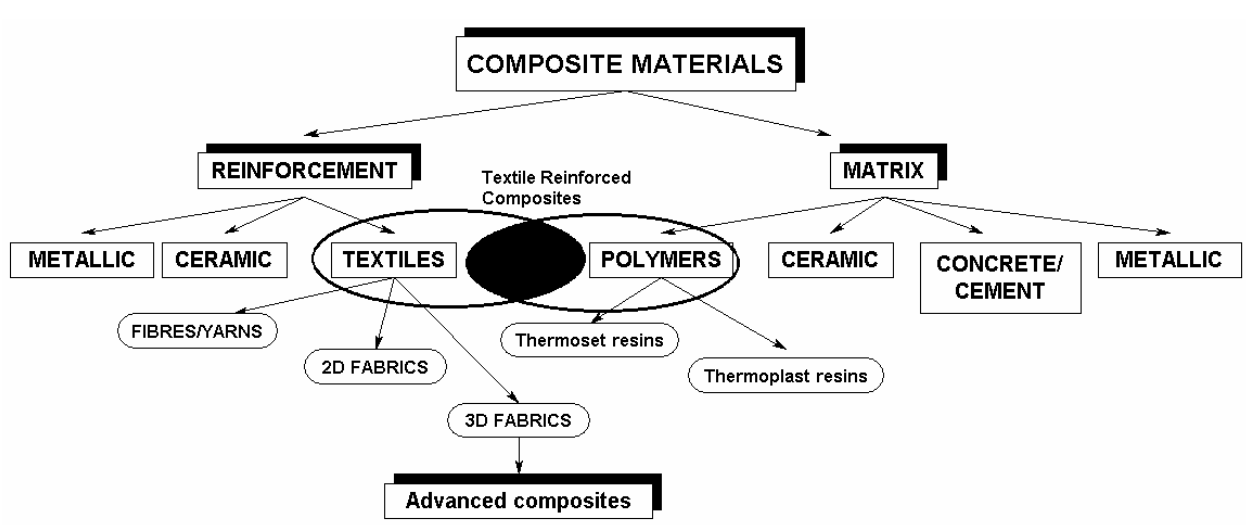


Fig. 1. Structure of composite materials

The development of textile reinforced composites (TRCs) with resin matrix is based on the desire to produce improved materials, with tailored properties. The textile material gives the ensemble strength, while the matrix ensures the composite unity and transmits the strains. The advantages of the textile reinforced composites are:

- controlled anisotropy of the textiles which means that their structure materials can be designed so that the fibres are placed on preferential directions, according to the maximum strain;
- the use of textile reinforcements allows to obtain a better weigh/strength ratio compared with the classic materials, such as steel;
- textile materials maintain their integrity and behaviour under extreme conditions – for example, they do not corrode in a outdoor environment, nor vary their dimensions when there are significant temperature variations, nor are they sensible to electro-magnetic fields;
- TRCs present an improved fatigue life.

The aeronautic industry was the first that used TRCs for airplanes. Currently, there is a high diversity of TRCs applications, with high economic impact (Mouritz, 1999). Composite materials can be found in all fields of technical textiles. Industrial applications of the composites include tanks, storage structures, pipes, hoses, etc. The automotive industry uses TRCs for car frames and other machine parts (manifold, wheels), while in aeronautics the composites developed from 1st level applications to 2nd level that refers to resistance elements in an airplane structure and the future trend is building one exclusively with composites. The composite materials also replaced traditional ones for the rotor blades of helicopters, increasing their life span and their resistance to wear (Mallick, 1997). One field of great interest for textile reinforced composites is the wind energy management – these materials are used to build wind mills. The TRCs are also used to produce sport equipment – tennis rackets, bicycles and motorcycles, etc.

An interesting application is in buildings, where composites (the so called Textile Reinforced Concrete) are used to reinforce walls (cement/concrete matrix), increasing their strength and reducing their thickness and subsequently production costs.

Classification of textile reinforced composites

Two main criteria can be used to characterise the textile reinforcements: the material structure/geometry and the technological process (Hu, 2008).

Fukuta et al. (1984) gives a classification of the textile reinforcement based on the significant dimensions of the textile material and its specific geometry. Fukuta considers not only the 3 dimensions, but also the preset fibres directions used in the material structure.

According to Scardino (1989), the textile reinforcements can be divided into 4 groups, depending on their architecture: discrete, continuous, with plane geometry and with spatial geometry, as illustrated in Table 1.

When considering the technological process, all textile processes can be used to produce reinforcement for composite materials, but the specifics of each type of process and the resultant material geometry lead to differences in possibilities and behaviour. The main processes employed in the production of textile reinforcements are: weaving, braiding, knitting and non-woven. Also there are other processes, such as filament winding and poltrusion, which process filaments. Most used reinforcements are woven fabrics (2D and 3D) and nonwovens (fibre mats), but the knitted fabrics, especially warp knitted structures, present a good development potential.

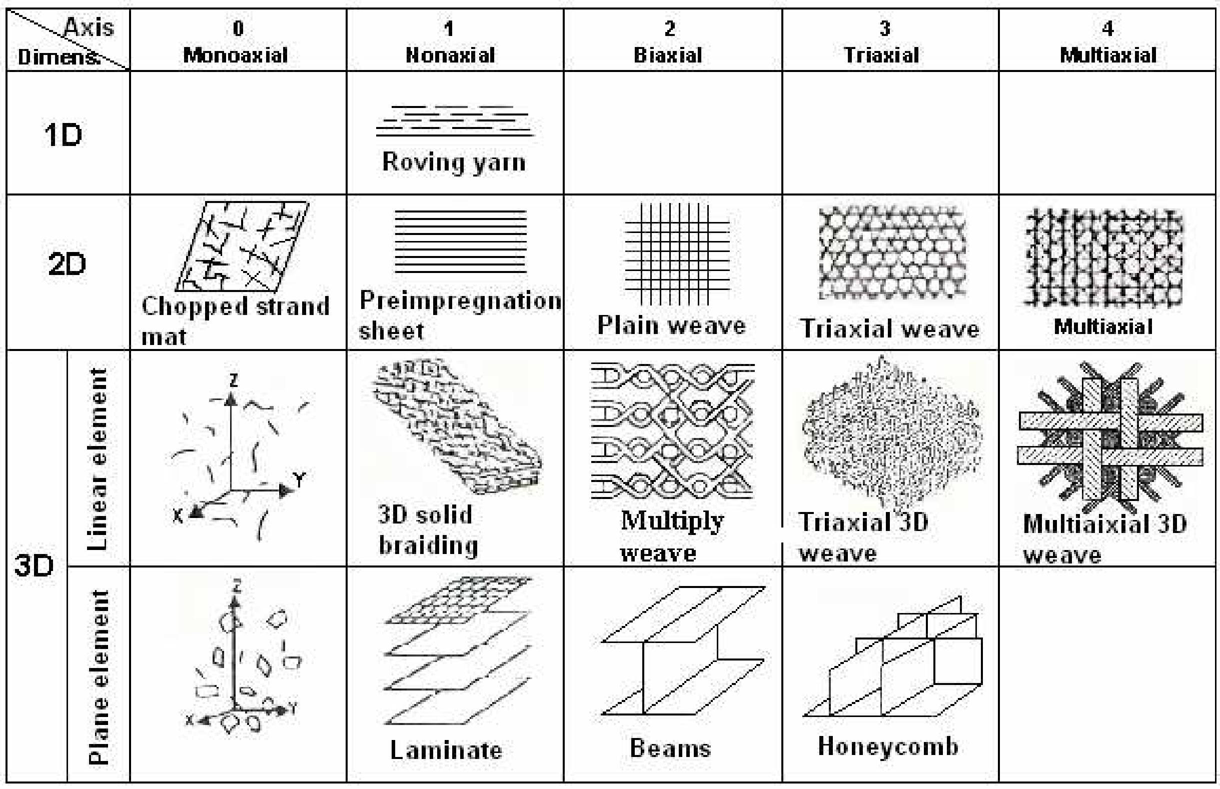


Fig. 2. Textile reinforcement systems, classification according to Fukuta et al.

Level	Reinforcement	Textile construction	Fibre length	Fibre orientation	Fibre entanglement
I	Discreet	Short fibres	Discontinuous	Uncontrolled	none
II	Linear	Filaments	Continuous	Linear	none
III	Plane	2D materials	Continuous	Planar	Planar
IV	Integrated	Advanced materials	Continuous	3D	3D

Table 1. Constructive classification of the textile reinforcements

The selection of a certain process is based on the architectural possibilities, the material characteristics and behaviour (dimensional stability, mechanic strength, drape and formability, etc) and its suitability with regard to the composite processing and its application.

Potential of knitted fabrics for composite reinforcement

The main advantages of knitted fabrics for composite reinforcement are:

- the possibility of producing knitted fabrics with 3D complex shapes
- improvement of fabric handling and matrix injection during composite processing
- acceptable processability of high performance fibres (glass, aramid, PES HT or HM)
- rapid manufacturing of knitted fabrics for reinforcements
- controlled anisotropy (yarn in-laid under preferential angles).

When considered in reference to other types of textile materials, knitted fabrics are not as well developed, mainly due to their lower mechanical properties (Leong et al., 2000). According to Verpoest et al. (1997), knitted fabrics present lower in-plane strength and stiffness in comparison to materials such as woven, braiding, non-crimps. Another problem limiting the use of knitted fabrics for composite reinforcement is the low value for volume fraction, due to the specific geometry of knitted stitches, characterised by areas without yarns.

The reduced mechanical behaviour is determined by the specific bending of fibres in the knitted stitches. Mechanical properties are controlled through fabric structure, structural parameters, yarn characteristics and process parameters. Structure is an effective way of improving properties by the use of float stitches and in-laid straight yarns placed under certain angles. Stitch density also affects the tensile behaviour and fabric stiffness,

Yarns are also important, their properties being transferred to the fabric level. The specifics of the knitting process make bending strength and rigidity the most important characteristics. This situation is essential, considering that high performance fibres are rigid and therefore must be processed carefully. Apart from carbon fibres, all other high performance yarns can be bent around a needle hook and transformed into stitches. The problems related to their processing are the fibre destruction and the modifications brought by the strains during knitting that lead to reduced mechanical characteristics of the fabric. The use of in-laid straight yarns eliminates the problem of fibre damage and also increases the volume fraction.

The multiaxial warp knitted fabrics, presented in part 3 of this chapter, are the most used for the production of composites. They have a laminar structure, with layers of yarns under preset angles, according to the application. The layers are connected and the risk of delamination is reduced.

Another development direction is the production of preforms with complex shapes for advanced composite materials. This is an interesting development direction, considering the complexity of the fabric architecture that can be achieved through knitting. The literature presents a significant amount of references concerning the development, characterisation and mechanical behaviour of these 3D fabrics.

2. Raw materials used for the production of knitted fabrics for advanced composite materials

Textile reinforcements are produced using high performance fibres, like glass, carbon/graphite, Kevlar, PES HM and HT, ceramic fibres, boron and silicon carbide fibres, etc. These yarns have superior mechanical behaviour that can meet the specific demands of composite applications that are illustrated in Table 2. They also have high bending rigidity that affects the knitting process and other characteristics that must be taken into consideration when designing a knitted reinforcement for composite materials (Miller, 1989).

Glass fibres (yarns, rovings) are the most common high performance fibres used to reinforce composite materials. They are characterised by hardness, resistance to chemical agents, stability and inertness, low weight and processability (Muckhopadhyay, 1994). There are more types of glass fibres depending on their chemical composition: E-glass, with good strength and high electrical resistivity, most common in composite materials; S-glass, with high tensile strength, most common in military applications; and C-glass, characterised by chemical stability and corrosion resistance.

	Fibre	Relative density [g/cm^3]	Young's Modulus [GPa]	Tensile strength [GPa]
1	Carbon (PAN)	2.0	400	2.0-2.5
2	Boron	2.6	400	3.4
3	E-glass	2.5	70	1.5-2.0
4	S-glass	2.6	84	4.6
5	Kevlar 29	1.44	60	2.7
6	Kevlar 49	1.45	60	2.7

Table 2. Main characteristics for some high performance fibres

Mechanically, the glass fibres are characterised by high strength, low elongation, high bending rigidity and brittleness. Law and Dias (1994) and Savci et al. (2001) showed that the glass fibres can resist when bent around the needle hook and therefore can be processed through knitting. Due to their brittleness and their low resistance to friction, the glass yarns damage easily, thus affecting the knitting process and subsequently the real strength of the reinforcement. Knitting glass fibre therefore requires a preliminary stage to determine the optimum technological conditions that ensure minimum fibre damage while maintaining the fabric quality. The fabric density, essential for the fibre fraction volume of the composite reinforcement gives this quality, together with the amount of fibre damage. High fibre fraction volume is a sine-qua-non requisite for the performance of the composite materials.

Experimental work

The experimental work is based on the direct study of the yarn after knitting, in order to identify the damage degree of the glass fibres inflicted by the knitting process. All models for the mechanical behaviour of the glass knitted fabric are based on the Young's modulus for the glass yarns. During the knitting process the filaments are damaged in a significant proportion, therefore altering the initial value of Young's modulus and altering the fabric properties. No previous study indicated the relation between technological parameters and the final value of the Young's modulus.

Two types of glass fibre were considered for the experiment: EC 11 408 Z28 T6 – Vetrotex and EC 13 136 Z30 P 100. The yarns are knitted using single jersey, as being the simplest possible structure.

The fabrics were produced on a CMS 320 TC (Stoll) flat machine with the following characteristics: gauge 10 E, negative feeding – IRO NOVA (Fig. 3) and holding down sinkers and presser foot (Fig. 4).

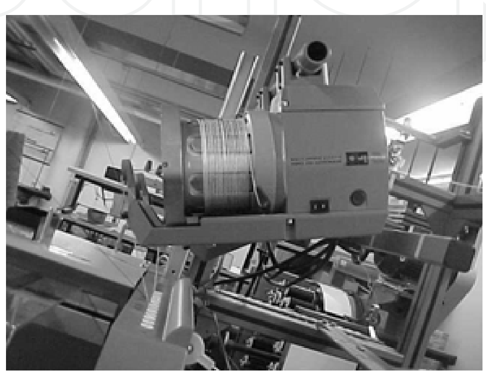


Fig. 3. IRO NOVA negative feeding

Fig. 4. Holding down sinkers and presser foot

In order to adapt to the yarn count, the fabrics are knitted with different values for the stitch quality cam, presented in Table 3. Each sample had 100 wales and 100 courses. The fabrics were relaxed until they presented no dimensional variation. The structural parameters (horizontal and vertical stitch density and stitch length) are illustrated in Table 4.

Yarn count [tex]	Quality stitch cam (NP)					Take down (WM)
	NP 1	NP 2	NP 3	NP 4	NP 5	
408	10.0	10.5	11.0	11.5	12.0	20
136	9.5	10.0	10.5	11.0	11.5	18

Table 3. Technological parameters used for knitting the samples

Yarn count [tex]	NP 2			NP 3			NP 4			NP 5		
	D_w [w/10 cm]	D_r [r/10 cm]	l_s [mm]	D_w [w/10 cm]	D_r [r/10 cm]	l_s [mm]	D_w [w/10 cm]	D_r [r/10 cm]	l_s [mm]	D_w [w/10 cm]	D_r [r/10 cm]	l_s [mm]
408	48	69	7.28	46	64	7.8	48	61	8.25	42	57	8.85
136	56	88	6.00	50	84	6.51	44	78	7.17	40	70	7.52

Table 4. Values for the structural parameters, in relaxed state

After relaxation 10 yarn lengths were drawn from the fabrics in order to determine their tensile properties, avoiding the edges, visibly more damaged then the rest. The tensile strength was tested on a HOUSENFIELD H10K-S (Tinius Olsen), according to ASTM 2256. According to previous studies, the glass yarns break in less than the minimum 20 seconds indicated by the standard. Therefore, the testing speed selected was the minimum value of 50 mm/minute. The data confirmed the breaking of the glass yarns less than 7 seconds.

Experimental results

Knitting conditions

Fig. 5 presents the aspect of a 408 tex glass fibre jersey fabric produced with the quality stitch cams in the limit position, in this case NP = 10.5. The destroyed filaments are placed more at the level of the sinkers loops and not at the level of the needle loops, as Law and Dias pointed out in their study. This situation sustains the idea of other cause for yarn damage than the tension peaks in the knitting point. Furthermore, the significant filament breakage repeats at every two courses, corresponding to the reverse carriage displacement when the needles receive less yarn. If the stitch length is even lower, the yarn gets out of the needle hooks and it can not be knitted. This situation is exemplified in Fig. 6, for a jersey fabric made of 136 tex glass fibres. The filaments appear to be completely destroyed, creating a plush effect.

Fig. 5. Aspect of the jersey fabric (408 text) knitted with NP1=10.5

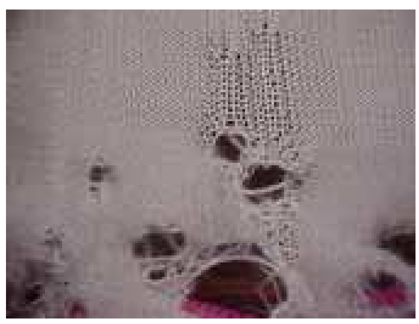


Fig. 6. Aspect of the jersey fabric (136 tex) knitted with NP1=10.5

Test results

The experimental results were calculated based on the raw data from the testing machine, according to the established methodology (ASTM D 2256), to obtain the following values: breaking strength, breaking tenacity, Young's modulus E, breaking elongation, breaking toughness and time to break. The results are centralised in Table 5. Yarn variant called Normal is the witness yarn, while the other variants are yarns knitted with a certain position for the stitch quality cam, defined in Table 3.

Yarn count [tex]	Yarn variant	Breaking force [N]	Breaking tenacity [cN/tex]	E modulus [N/tex]	Breaking elongation [%]	Breaking toughness [J/g]	Time to break [sec]
136	Normal	75.67	55.59	27.37	2.2	6.64	6.89
	NP 3	23.59	17.27	14.79	1.38	1.45	4.14
	NP 4	30.92	22.73	18.26	1.42	1.93	4.24
	NP 5	37.51	27.58	21.24	1.55	2.47	4.66
408	Normal	229.87	56.34	84.65	2.46	6.86	6.76
	NP 2	118.73	29.10	61.18	1.87	3,01	5.60
	NP 3	156.59	38.37	69.52	2.00	4.29	6.01
	NP 4	165.05	40.45	70.08	2.12	4.86	6.38
	NP 5	167.83	41.14	71.66	2.15	4.87	6.44

Table 5. Experimental results for tensile testing

Discussions

Contrary to Law and Dias, the experience of knitting on flat electronic machines showed that the needle could be pulled inside its channel without restrictions for the lowest point. The relation filament breaking – stitch length was found to be opposite to the one presented by Law and Dias. For each yarn count there is an inferior limit for the stitch length, guaranteeing the quality of the fabric. For this limit the degree of filament breaking is so high the yarn is almost completely destroyed and will break when unravelled from the fabric. It is the case of the 136 tex yarn knitted with NP2 stitch cam position. No tensile tests were performed for this variant and therefore it was not included in the experimental data.

The differences in strength and tenacity, compared to the normal values, show that the knitting process has a negative influence on the tensile properties. Furthermore, the decrease in strength is in a direct correlation with the stitch length – the lower the stitch length, the lower the tensile properties. Figs. 7 and 8 present the representative graphics for each type of yarns, illustrating the variation of the breaking force with the elongation.

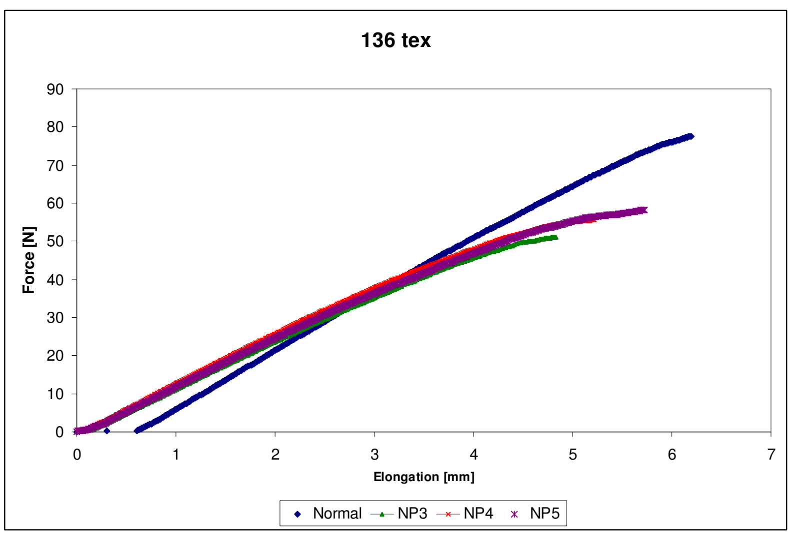


Fig. 7. Force-elongation curves for the EC 13 136 Z30 P 100 glass yarn

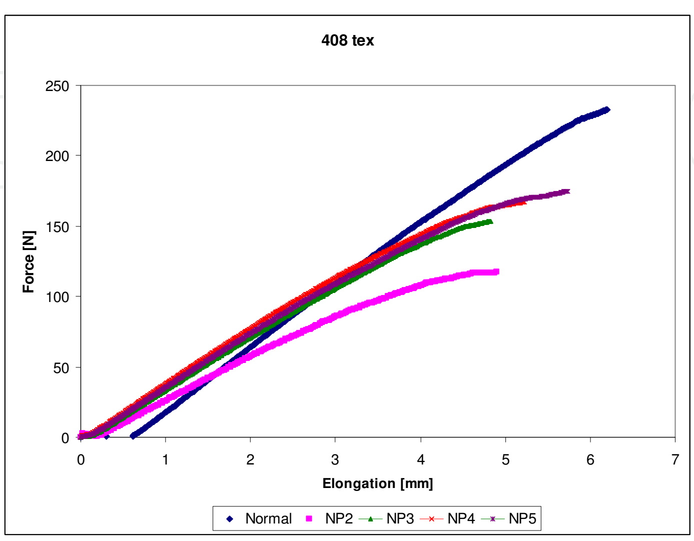


Fig. 8. Force-elongation curves for the EC 11 408 Z28 T6 glass yarn

The experimental data and the graphics are showing a contradiction with Law and Dias, concerning the cause of filament breakage during knitting. If the tension occurring in the looping point is responsible for the filament damage, then higher stitch length should present higher values for the breaking force, but the experimental results contradict this. One answer for this different opinion could be the feeding mechanism. In this case, the yarn was fed using an IRO NOVA feeding device, ensuring the proper quantity of yarn for the process. Without it, knitting proved impossible.

The breaking phenomenon appears due to the friction between the yarns and the knitting elements, especially the knock-over plates that can act like knifes during rob back stage. The longer the stitch length, the smaller the tension in yarns and there is less filament damage.

The differences between the normal values and the ones for the knitted yarns 136 tex are varying from - 71% in case of the smallest stitch length and - 55% for the highest stitch length. In the case the 408 tex yarn, the difference interval is - 48.34% to - 26.99%.

The decrease in breaking toughness is more significant, as illustrated in Fig. 9. The toughness value for the 136 tex NP2 variant was introduced and was considered 0 only for comparison purposes. When compared, the initial toughness values for the two yarns are similar, but the 136 tex yarn shows a much higher decrease in breaking toughness then the other yarn. The decrease interval for 136 tex is extremely high 78-63%, while for 408 tex the decrease is in the interval 56-29%.

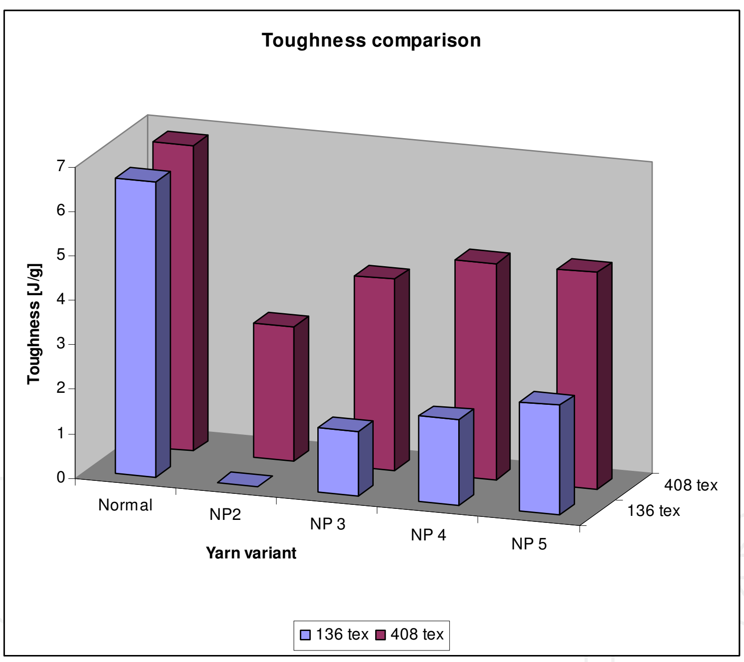


Fig. 9. Influence of yarn count and filament damage on breaking toughness

This situation suggests the influence of the number of filaments in the yarn, and also the fact that the amount of filament damage on the knitting machine is the same, regardless of the yarn count. A superior number of filaments ensure a better knittability, the yarn maintaining better tensile properties.

The breaking force and toughness values determined for the yarns knitted with NP4 and NP5 stitch cam positions are similar indicating that filament damage amount is the same. Even if the best properties are obtained for the highest stitch length – corresponding to NP5 value for the quality cams, this must be balanced with the fabric density, essential for the overall performance of the fabric in the composite material. Therefore, the optimum technological parameters appear to be those for the fourth situation, with NP4 value for the stitch quality cam. In practice, even if the strength level is lower, value NP3 can also be used, due to the higher fabric density.

3. 3D knitted structures

In the case of knitted fabrics, the 3D architecture is facilitated by their high extensibility and formability that allow the production of complex shapes. This is the reason why the knitted fabrics are regarded as a viable option for preforms for advanced composite materials.
The main advantages of the 3D knitted fabrics are:

a. the high formability of the fabrics, especially due to their drape characteristics
b. the high complexity of the shapes that can be produced;
c. the use of existing technology, without major adaptations;
d. knitted fabrics exhibit good impact behaviour.

Knitted three dimensional performs are less studied and used, mostly because the following problems related to their production and their properties:

a. the development of these fabrics is still at laboratory stage;
b. the mechanical characteristics of the resulting composites are at a lower level and require improvement;
c. the specific properties and their prediction are not yet well developed, mainly because of the complexity of the knitted fabrics;
d. the pretension of the perform before its impregnation with resin determines a uneven behaviour for the final composite due to fibre migration in the stitches.

The 3D knitted fabrics can be divided into three main groups: multiaxial fabrics (multilayer), sandwich/spacer fabrics and knitted fabrics with spatial geometry (spatial fashioned).

Multiaxial fabrics

The multiaxial fabrics are characterised by the presence of multiple layers of yarns disposed at preferential angles that are assembled in the knitted fabrics. These fabrics are produced on special warp knitting machines using glass fibre or carbon fibre for the layers. The warp knitting technology is best suited for this kind of structures with in-laid yarns. Multiaxial fabrics are used mostly for the reinforcement of composite materials.

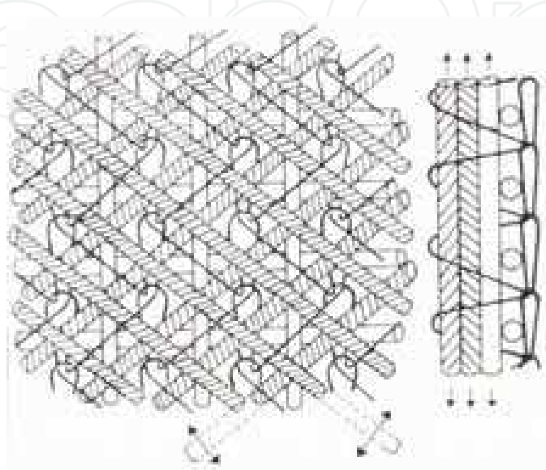


Fig. 10. Structure of the multiaxial knitted fabrics

The different layers of yarns in the multiaxial warp knitted fabrics are independent and the yarns fed under preset angles: 0^0 (weft yarns), 90^0 (warp yarns) and any value between these, like +/- 30^0 and +/- 45^0. The layers are united by the actual knitted fabric, using pillar or tricot stitches, as exemplified in Fig. 10 (Raz, 1989).
The preset angles correspond to the directions requiring higher strength during use and are imposed by the application. Currently, there are two main technologies adapted for the production of multiaxial fabrics: the Karl Mayer technology and the Liba technology.

a. Karl Mayer technology

The Karl Mayer machine uses four yarn systems – one to produce the ground fabric, one to insert the warp yarns, one for the weft yarns and the fourth for the yarns disposed under a preset angle. The inclined yarns are fed with two guide bars that have a rotational movement of 1 pitch every row. The guides are shogged in only one direction, passing from one bar to the other, changing the yarn direction within the fabric structure, as illustrated in Fig. 11.

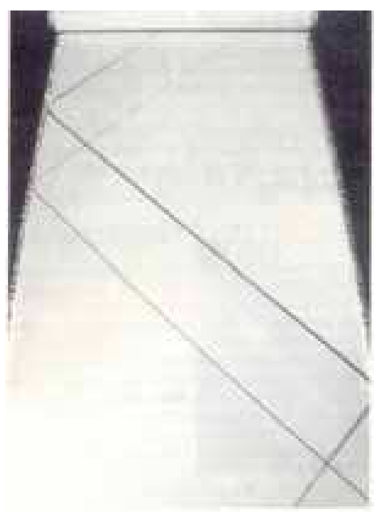


Fig. 11. The modified angle when changing direction in a Karl Mayer multiaxial fabric

The advantages of the Karl Mayer system are: the accuracy of the inclined yarns position, the fact that the needles do not destroy these yarns and the high productivity. Still, the fabrics are less compact affecting the fabric mechanical behaviour.

b. LIBA technology

The Liba technology is by far the best adapted to produce multiaxial fabrics. The MAX 3 CNC machines use a Copcentra machine that is preceded by a number of 3 zones where the layers are formed with the help of carriers feeding the yarns under the desired angle along the table: 0^0 for the weft yarns and 26^0 to 60^0 for the rest. The warp yarns (90^0) are introduced in the knitting zone, using special guides. The layers are brought to the knitting zone and connected using pillar or tricot stitches. A non-woven mat (chopped glass fibres) can also be inserted, if the application requires it.
Fig. 12 illustrates the Liba system (source: www.liba.de). Liba also developed such a system also for carbon fibres (Copcentra MAX 5 CNC), where the carrier course is modified in order to reduce fibre waste.
The system allows obtaining fabrics with different degrees of compactness, made of different raw materials, as exemplified in Fig. 12 (source www.liba.de). The risk of fibre

destruction caused by the needles penetrating the layers is eliminated through the walking needle technique, where the needle bed is moved together with the layers.

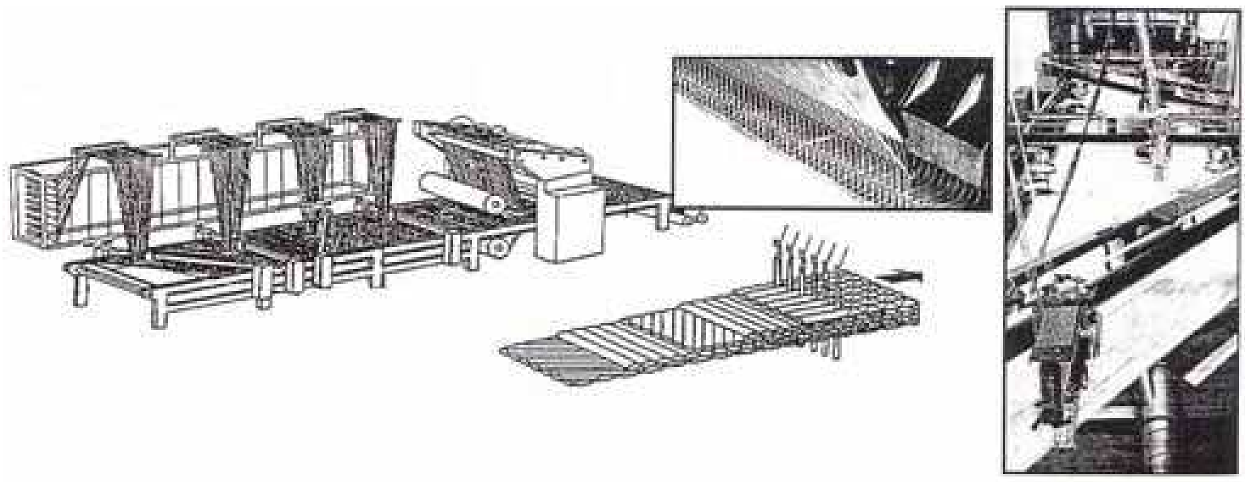
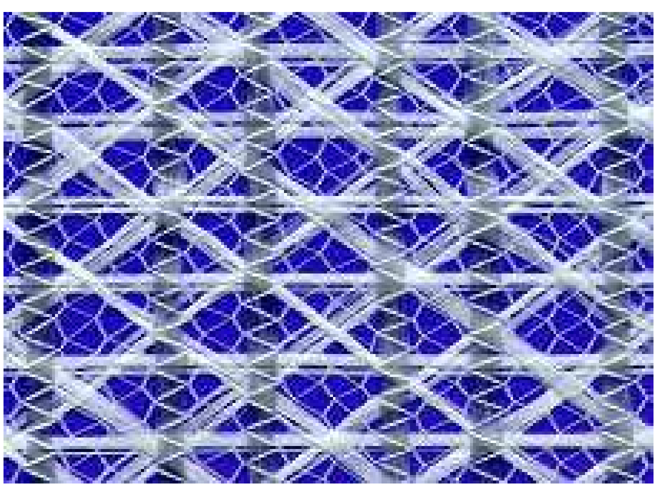
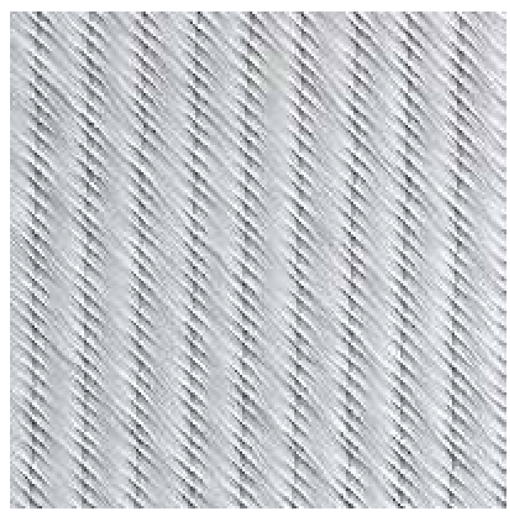


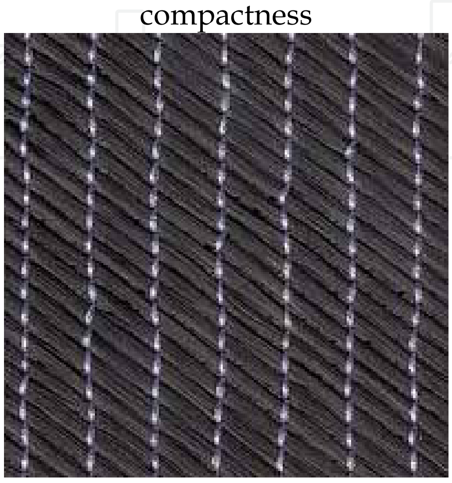
Fig. 12. Liba CNC machine for multiaxial fabrics



Glass fibre multiaxial fabric with low degree of compactness



Glass fibre multiaxial fabric with high degree of compactness



Multiaxial fabric made of carbon fibre

Multiaxial fabric made of Kevlar fibre

Fig. 13. Examples of multiaxial fabrics

Spatial fashioned knitted fabrics

The 3D knitted performs started to be developed in the '90, mainly based on the development of electronic flat knitting machines and CAD/CAM systems. Even if there is significant progress in this domain, there are a lot of aspects that need addressed in order for the spatial knitted fabrics to become industrially feasible.

The spatial fashioning of the knitted fabrics is based on the need to produce fabrics with complex shapes that are similar to the shape of the final product. Even if a certain degree of spatial geometry can be obtained by using modules of structures with different patterns or by dynamic stitch length, the technique of spatial fashioning is the only one that has no limitations with regard to the shape complexity and dimensions. This technique (also known as 'flechage') is based on knitting courses on all working needles and courses on a variable number of needles, determining zones with different amount of stitches. The zones with the highest amount of stitches will have in the end a spatial geometry.

A classification of the spatial fashioned fabrics must take into consideration the 3D shape of the product, defined geometrically as a 3D body. These bodies can be divided in solids of revolution, such as tubes (cylinders), spheres and hemispheres, cones and frustum of cones, ellipsoids, hyperboloids, and polyhedrons, such as tetrahedrons, pyramids, parallelepipeds, etc. Apart from these simple bodies, other bodies can be considered: bodies obtained from composing simple bodies or bodies with irregular shape.

The fabric 2D plan is a rectangular area where are positioned fashioning lines that define the final 3D shape of the product. Such a 3D fabric is obtained by placing more fashioning lines with certain characteristics, forming repeating geometric basic forms within the plan or not (as is the case for parallelepiped forms).

The **fashioning lines** can be defined as the zones where the knitting will be carried out on a variable number of needles, these zones generating the spatial geometry. The lines have two components, corresponding to decreasing the number of working needles and the other to increasing them. In the fabric, these two lines become one, the actual fashioning line, as presented in Fig. 14.

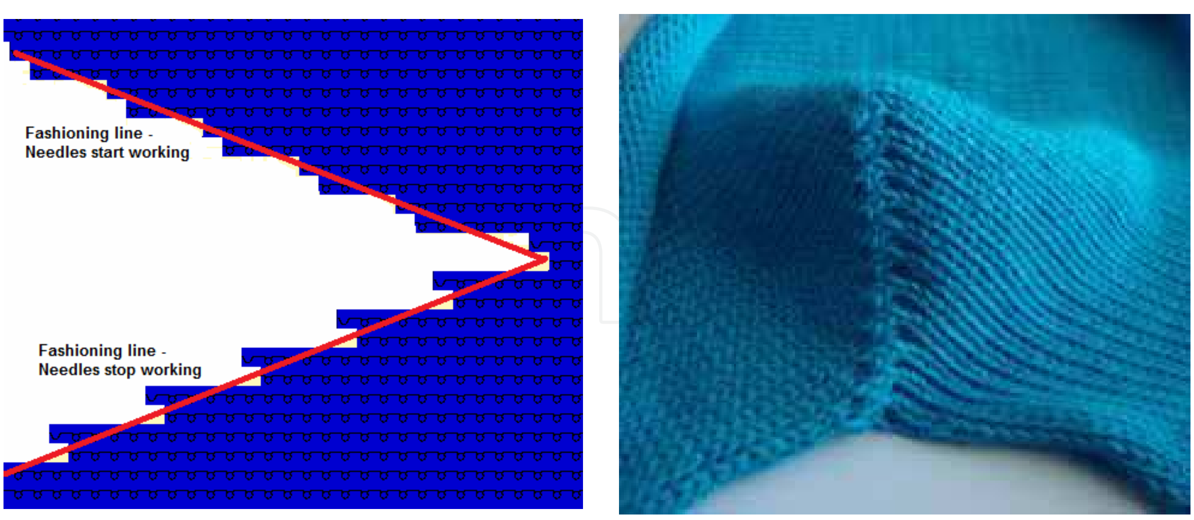


Fig. 14. Fashioning line - in the knitting programme and in the fabric

Fig. 15 illustrates the correlation between the 3D shape of the product and the 2D plan of the fabric, emphasising the most significant elements for the knitting process design. The evolute of the 3D body is obtained using sectioning lines and is the same with the 2D plan of the fabric that contains the fashioning lines. The knitting direction is very important when designing a

3D fabric. Knitting along the transversal or longitudinal direction of the final shape determines the knitting programme, the plan aspect and furthermore the specific behaviour of the fabric in the product. In some cases, only one knitting direction with regard to the product shape is possible, the other option being technologically not feasible. Other limitations concern the positioning of the fashioning lines within the fabric and their dimensions.

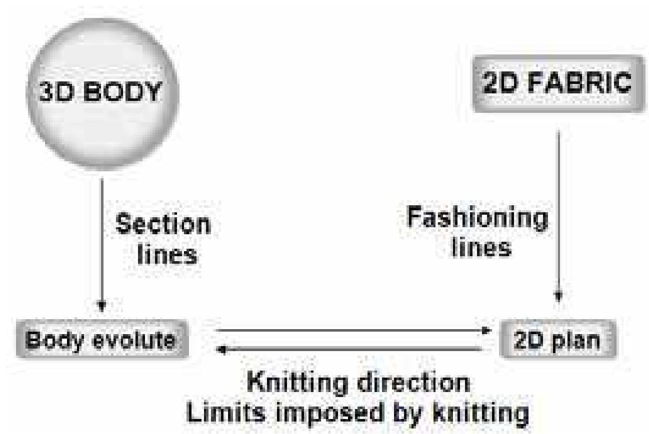


Fig. 15. Correlation between the 3D body and the knitted 2D fabric

Some of the most representative examples are illustrated in Figs. 16 to 20, presenting the 3D shape and the fabric 2D plan.

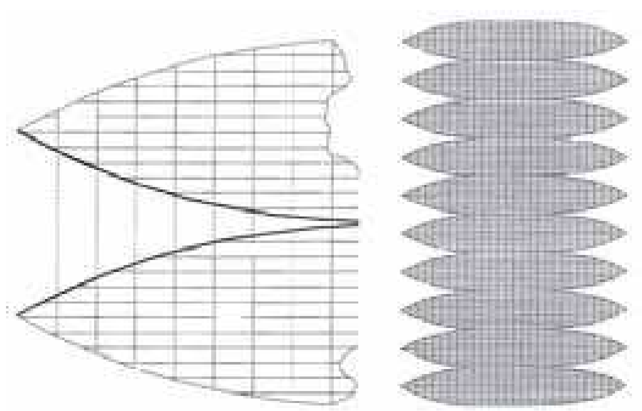


Fig. 16. (Hemi)spherical shape (Cebulla et al., 2000)

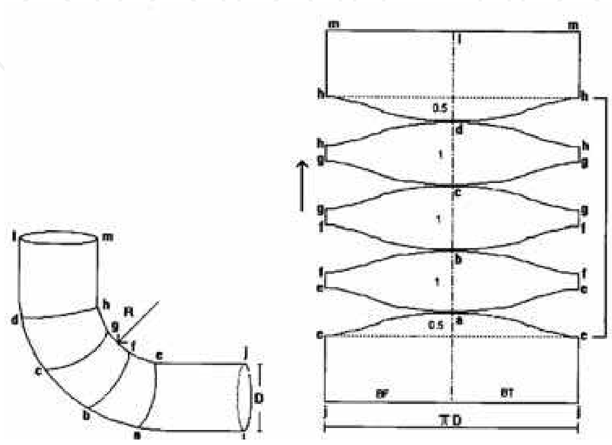


Fig. 17. Bent tubular shape (Song et al.)

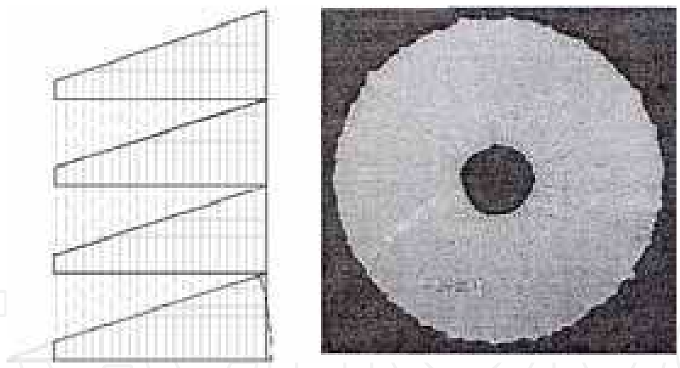


Fig. 18. Discoid shape (Cebulla et al., 2000)

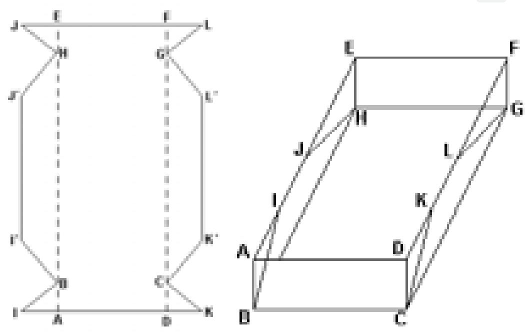


Fig. 19. Parallelepiped shape (Dias, 2000)

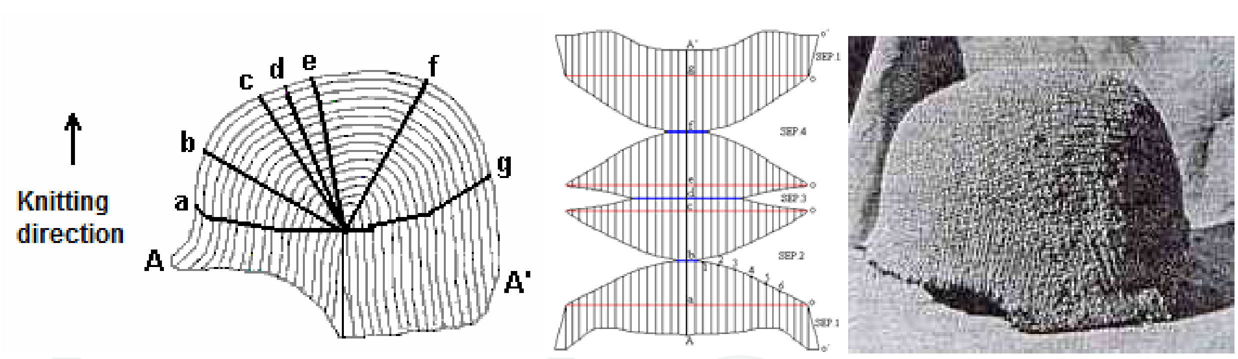


Fig. 20. Helmet made of aramid fibres – theoretical form, 2D fabric and final preform (Araujo et al., 2000)

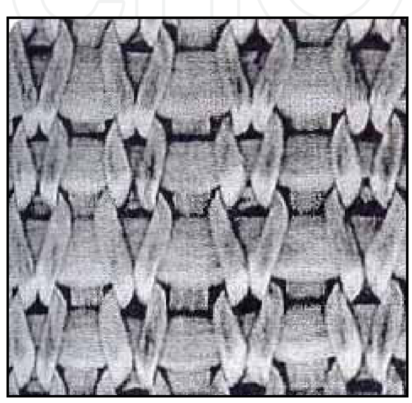


Fig. 21. Jersey fabric reinforced with weft and warp yarns (Cebulla et al., 2000)

There are some issues related to the fashioned fabrics used as preforms. One is the fabric strength, considering that the weft knitted materials exhibit limited mechanical characteristics. The solution to this problem is to insert warp and weft yarns within the structure. Fig. 21 presents a jersey fabric with warp and weft yarns, produced on a flat machine with adapted yarn feeder for the warp yarns (Cebulla et al., 2000). Apart from giving the fabric strength, it also improves the volume fraction of the reinforcement, increasing the quality of the composite materials.

Sandwich/spacer fabrics

A sandwich/spacer fabric is a 3D construction made of two separate fabrics, connected in between by yarns or knitted layers (Ciobanu, 2003). The fabric thickness determined by length of the connecting yarns/layers.

When produced on warp machines, these fabrics are known as spacers. They are obtained on double needle bar machines, with 4 to 6 guide bars – 1 or 2 guide bars produce the independent fabrics by knitting only on one bed and the middle bars create the connection by working on both beds (forming stitches or being in-laid). The fabric thickness depends on the distance between the two beds (spacer distance).

Fig. 22 exemplifies a spacer fabric made of glass fibre. An interesting application for spacer fabrics are the so called textile reinforced concrete that is used in buildings. Liba designed a double needle bar Raschel machine model DG 506-30-2HS that produces spacer fabrics with net structure, as illustrated in Fig. 23. The fabrics present weft and warp in-lays that form the net geometry and give the fabric strength on both directions (source: www.liba.de).

Fig. 22. Spacer fabric made of glass fibre

Fig. 23. Net spacer used for textile reinforced concrete

In the case of weft knitted fabrics, they are known as sandwich fabrics. Even if they can be produced also on circular machines (connection with yarns), they are mainly produced on electronic flat knitting machines that offer the required technical conditions and the development possibilities.
The connection can be generated through yarns fed on both beds or by knitted layers. The first solution is limited with regard to shape complexity and fabric thickness. The second connecting principle requires knitting separately on the two beds and at a certain point to stop and knit the connection layer on selected needles, usually 1x1. These needles can work also for the separate fabrics (if the length of the layer is small enough), or can be used exclusively to produce the connection, if the length and/or the shape complexity require (Fig. 24).

Fig. 24. Sandwich fabric with connecting knitted layers

There are two types of connecting layers (Araujo et al., 2000):

- Single layers (Fig. 25.a) – the layer is produced on one bed (jersey) or on both beds (rib, interlock) and can have a perpendicular or an inclined disposition between the separate fabrics.
- Double layers (Fig. 25.b) - two layers are knitted separately on the beds, connected at a certain point with a rib evolution; if a specified amount of rib courses will be produced also in the exterior fabrics, then the connection will be "X" shaped, with possibilities to extend more the rib dimensions or to alternate the disposition of the two layers.

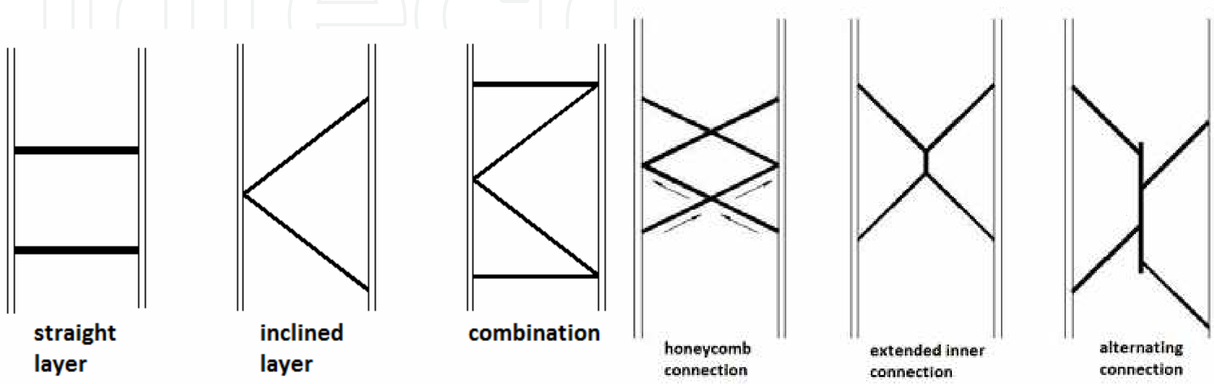


Fig. 25. Types of connecting layers

The sandwich fabrics presented are characterised by constant thickness and rectangular form in cross section. There are three major ways to diversify these fabrics and to obtain structures with complex shape (Ciobanu, 2003):

- The use of connection layers with different length
- The use of connection layers with variable form (the fashioning/flechage technique)
- The use of exterior fashioned separate fabrics

Sandwich fabrics with connecting layers of different length

The simple variation of the layer length will modify the cross-section of the fabric. The shape is created by the specific position of the separate fabrics between the consecutive layers. Two possibilities can be mentioned. One takes into consideration a specified sequence of layers with different length, as illustrated in Fig. 26. The different length of the layers will determine an inclined geometry for the exterior fabrics.

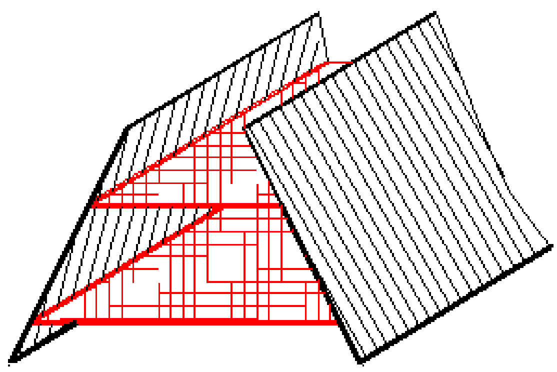


Fig. 26. Sandwich fabric with connecting layers of variable length

The other possibility refers to a sequence of two layers with predetermined (different) length, combined with an according number of courses in the separate fabric(s) that generates a corner effect (position at 90^0). It is the case of fabrics with L and T shapes, presented in Fig. 27 and Fig. 28.

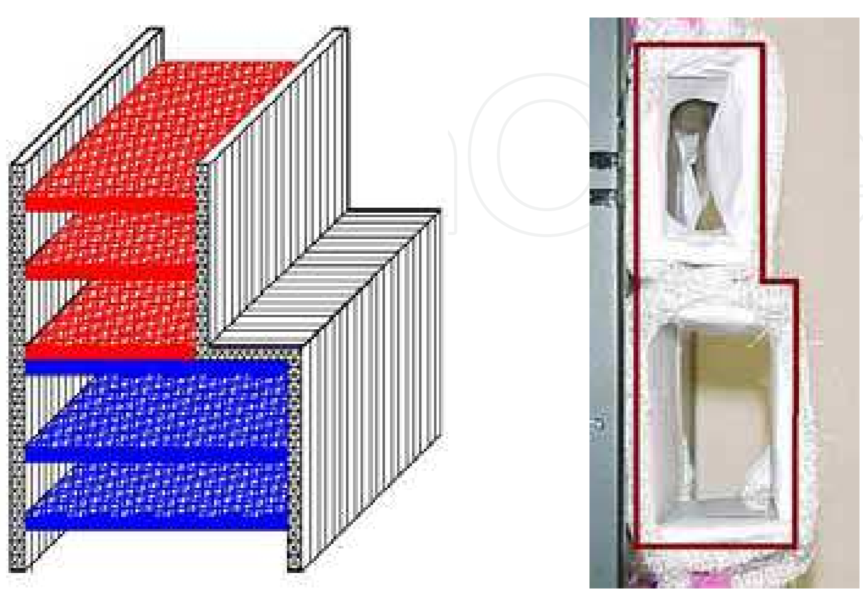


Fig. 27. Sandwich fabric with L shape

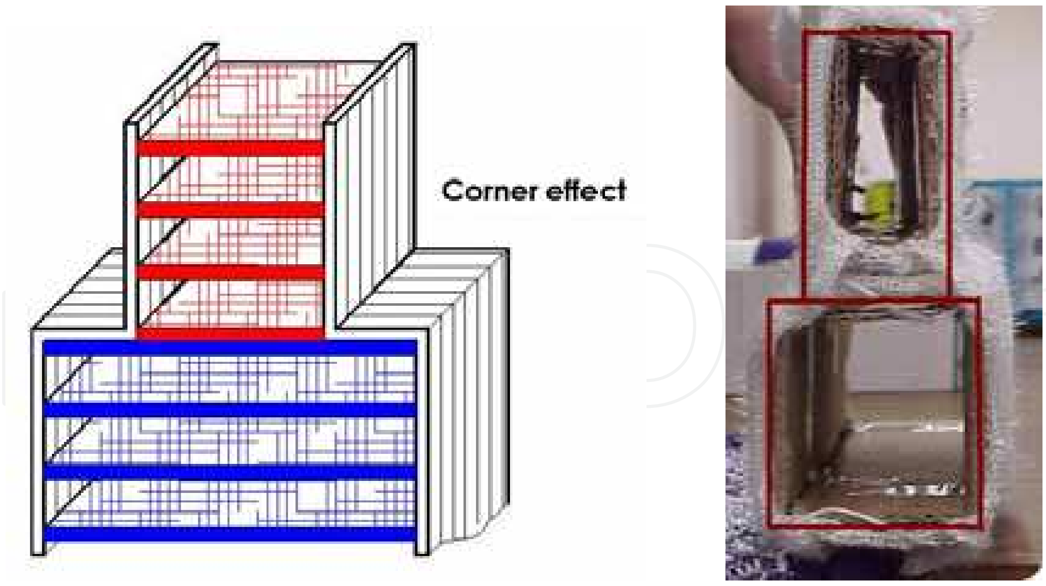


Fig. 28. Sandwich fabric with T shape

Sandwich fabrics with shaped layers (variable courses technique)

In this case the shape is determined directly by the shape of the layers, obtained through the variable courses technique. The technique is based on knitting on only a part of the needles producing the layer, in certain rows, while the others are missing. One example (knitting programme, Sirix) is presented in Fig. 29.

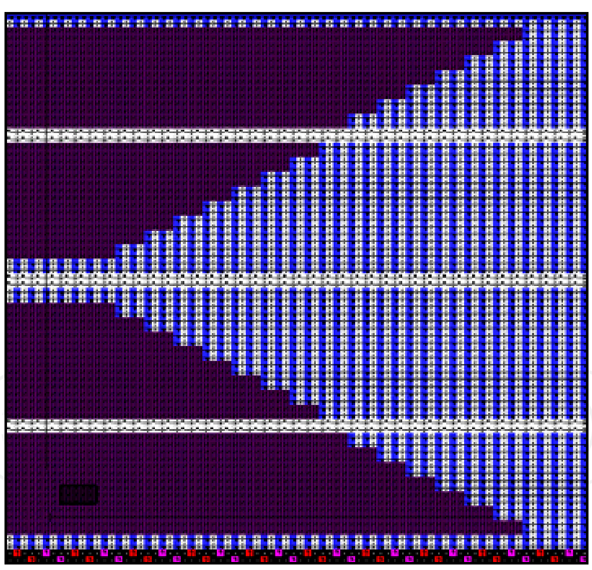
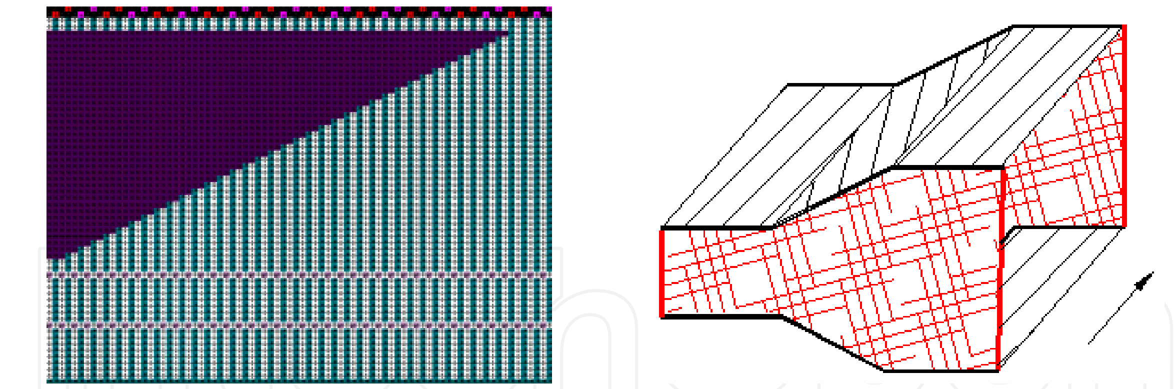
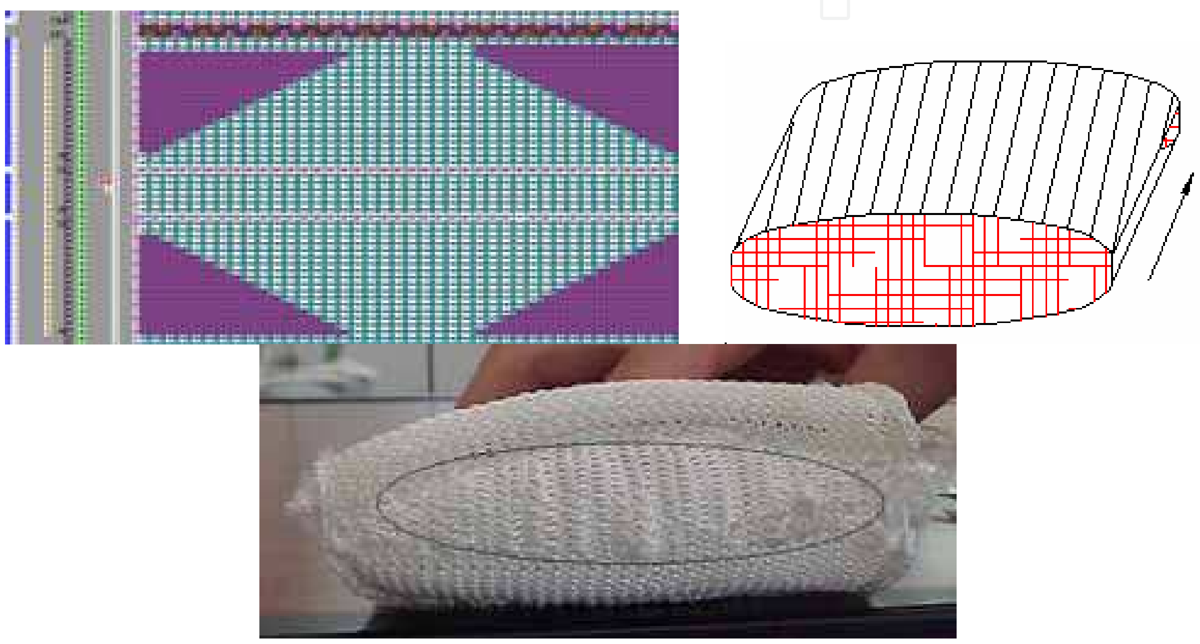


Fig. 29. Knitting sequence for a shaped layer (SIRIX, Stoll)

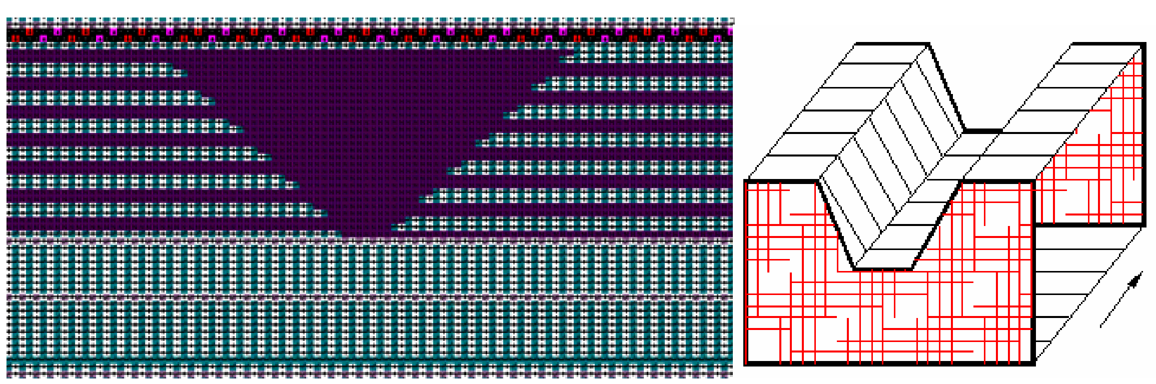
The fabric cross section given by the connecting layers is controlled through these layers. Different shapes can be therefore produced, as exemplified in Fig. 30. The layers are emphasised in red, while the separate fabrics are lined; the arrows are indicating the knitting direction. Two main types of shaped layers can be identified: with integral shape (the yarn guide is feeding continuously, even if on only a variable number of needles), as in Fig. 30.a. and b. and with divided shape (the evolution is split on distinct groups of needles, requiring separate feeding), as in the case of the fabric presented in Fig. 30.c.



a) Sandwich fabric with trapezoidal cross section



b) Sandwich fabric with elliptical cross section



c) Sandwich fabric with complex cross section

Fig. 30. Examples of sandwich fabrics with shaped connecting layers

Sandwich fabrics with fashioned exterior fabric

The fully-fashioning of the separate fabrics is obtained by narrowing and enlargement technique the number of working needles of the fabrics, using stitch transfer and racking. Fig. 31 illustrates one such possibility.

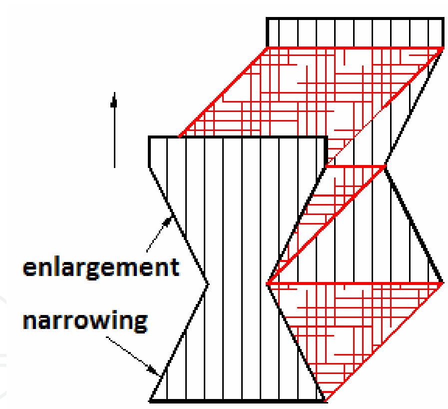


Fig. 31. Sandwich fabric with fashioned exterior fabrics

4. Application example – knitted preform for airplane wing

The application presented in the paper refers to a knitted preform for an airplane wing (glider). It was intended to knit a 3D shape identical to the wing. The preform was used to produce the composite material (through RTM).

Type and geometry of the knitted preform

The airplane wing prototype was defined using NACA 4 digital profile, according to specifications. Fig. 32 presents the geometry and dimensions of the chosen profile.
The wing is characterised by the following aspects:

- A difference in width between the beginning and the end of the wing – that requires successive narrowing;
- The difference between the two extremities is 60 mm, determining the narrowing slope;
- The fabric thickness for the outer layer is 5 mm;
- There are two interior walls with 5 mm thickness and different heights, according to the wing cross section: 79 mm – for the higher wall, and 64 mm – for the smaller wall.

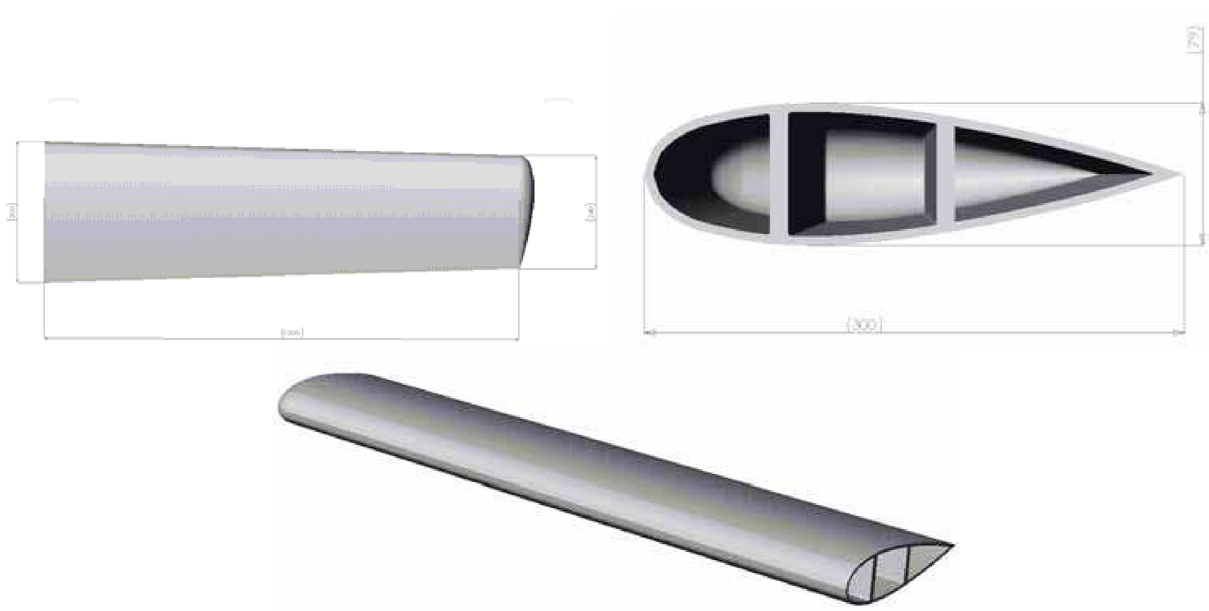


Fig. 32. Wing geometry and dimensions

Constructive, structural and technological characterisation of the preform

The complexity of the wing shape required the production of the knitted preform on a flat weft knitting machine, due to their advantages mentioned before.

The preform was knitted on a CMS 320 TC Stoll machine, using EC 11 408 Z28 T6 (Vetrotex) glass fibre. The yarn was tested on a Housenfield (Tinius Olsen) testing machine model H100 KS in order to determine its mechanical properties. The yarn is characterised in chapter 2 of this work.

The production of a preform that includes the inner walls requires a sandwich structure with connection through single knitted layers, according to the dimensions defined above. A very important aspect is the knitting direction that is determined in this case by the position of the inner walls. In the preform, the inner walls are created by the connecting knitted layers. Choosing another knitting direction, perpendicular to the one considered is not a viable solution due to the fact that this way the inner walls (connecting layers) are impossible to knit. Fig. 33 illustrates the architecture of the knitted preform. The zones marked on the drawing represent:

- border – 1 x 1 rib on selected needles;
- initial zone –1 x 1 rib – this is the part where the rib evolution is produced on all needles and the feeder for the glass yarn is not yet working; it is subsequently removed, together with the border;
- beginning zone – first zone in the preform, corresponding to its inclined inferior extremity;
- zone I – zone made only of the outer fabrics up to the first inner wall (connecting layer);
- zone II – zone of the outer fabrics between the inner walls;
- zone III – zone of the outer fabrics up to the beginning of the inclined superior extremity;
- ending zone – zone corresponding to the superior extremity.

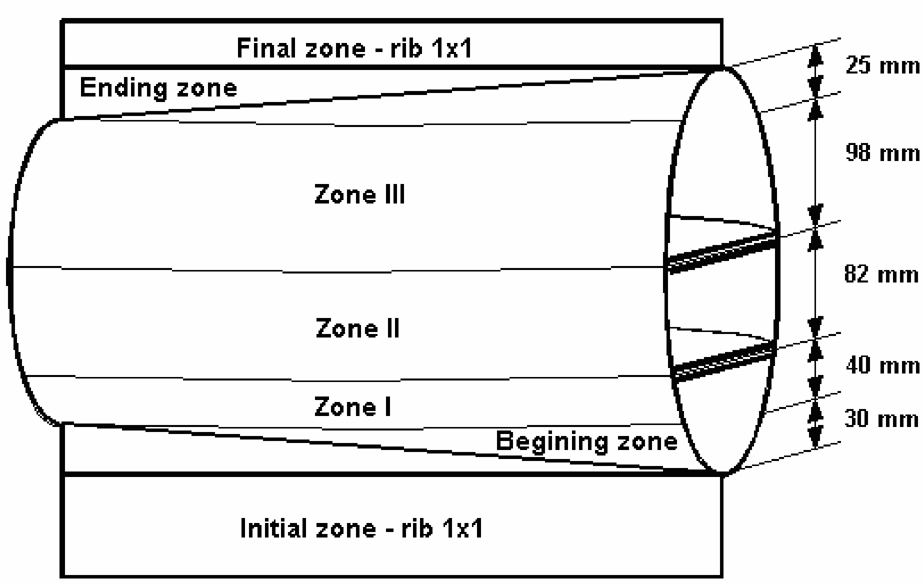


Fig. 33. Architecture of the knitted preform

The lateral edges of the preform must also be characterised, the lower edge being closed and shaped, while the wider edge is open and straight.

In the case of the considered knitted sandwich structure, both the outer fabrics and the inner walls are knitted on selected needles (1x1). A tubular evolution on selected needles with fleece yarns can be used in order to increase the fabric compactness (see Fig. 34). The main problem with last structure is the positioning outside the fabric of the floating fleece yarns that generates an irregular plush aspect, and also increases the snagging. Still, the simple pretension of the fabric, specific to the production of the composite material eliminates this situation.

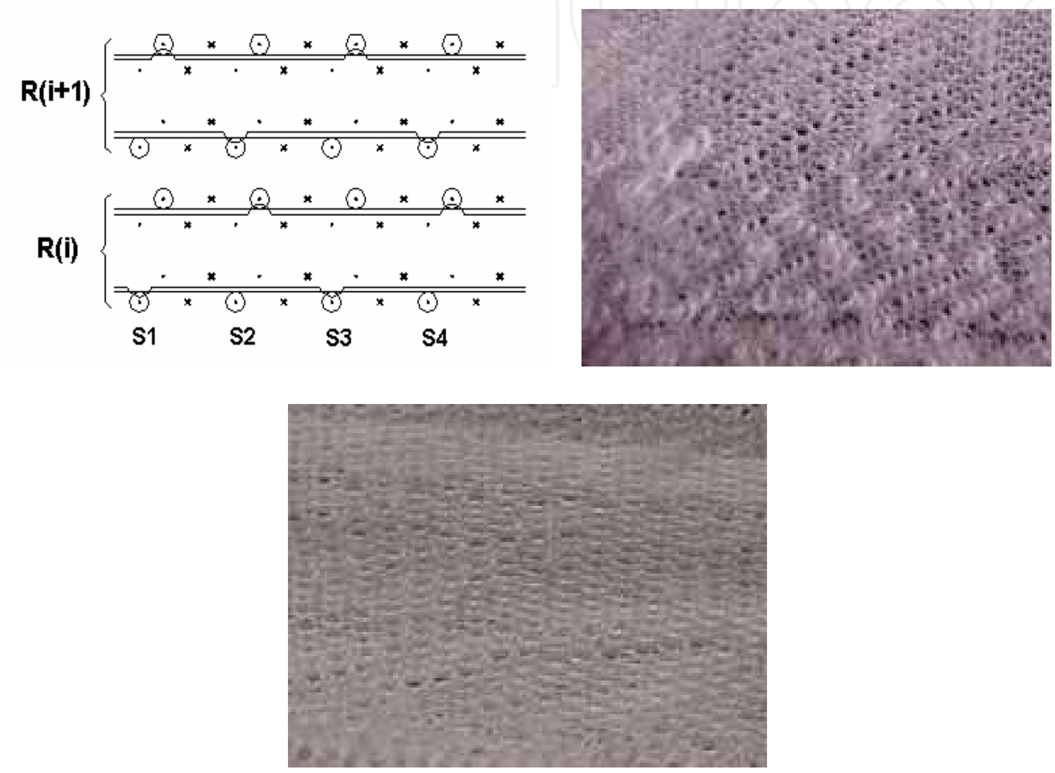


Fig. 34. Tubular evolution on selected needles with fleece in-lay – fabric aspect relaxed and stretched

Table 6 presents the values of the main structural parameters for the two structures (simple tubular on selected needles and tubular on selected needles with fleece yarns).

<table>
<tr><th rowspan="2">Structure</th><th colspan="2">Stitch density</th><th rowspan="2">Stitch pitch A, [mm]</th><th rowspan="2">Stitch height B, [mm]</th><th rowspan="2" colspan="2">Stitch length l_{stitch}, [mm]</th><th rowspan="2">Weight M/m^2, [g]</th></tr>
<tr><th>D_w [wales/50mm]</th><th>D_r [rows/50mm]</th></tr>
<tr><td>Tubular, on selected needles</td><td>16</td><td>26</td><td>3.12</td><td>1.92</td><td colspan="2">9.6</td><td>842</td></tr>
<tr><td>Tubular, on selected needles, with fleece yarns</td><td>12</td><td>25</td><td>4.17</td><td>1.92</td><td>10.3</td><td>4.7</td><td>950</td></tr>
</table>

Table 6. The values of the main structural parameters for the knitted fabrics

Beginning and ending zones of the preform

The difference in width between the two extremities can be obtained through more knitting sequences. One possibility is to produce some zones that will be subsequently removed. In these zones the evolution is successively changed from 1x1 rib to tubular jersey, specific to the sandwich structure. The use of two feeders for the tubular fabric (row 2) requires 1x1 rib evolutions on selected needles that present the disadvantage of larger floats. To avoid this situation, the 1x1 rib evolutions on selected needles can be maintained only for small zones, the rest of the working needles producing tubular evolutions (see Fig. 35). Such a variant presents the advantage of simplifying the knitting sequence and the process.

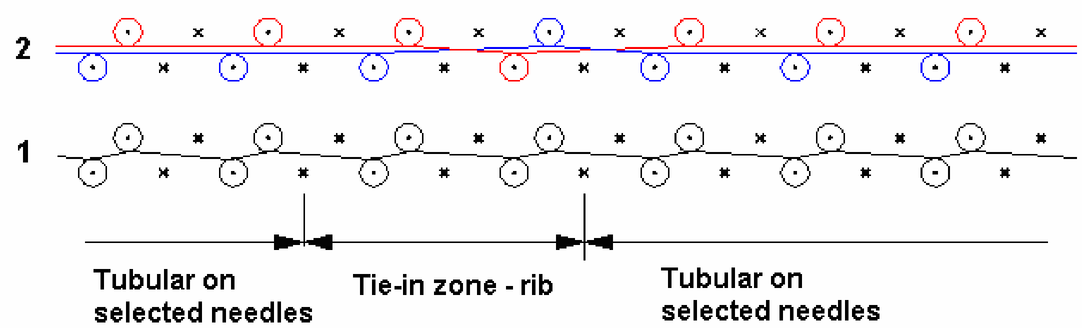


Fig. 35. Tie-in zone – from tubular to rib on selected needles (beginning zone)

Fig. 36 illustrates a fashioning solution for the beginning and ending zones. In this case, a number of incomplete rows are knitted with tubular evolution, using one yarn feeder. The groups of needles are successively introduced to work until all active needles are working. This way, the supplementary zones to be subsequently eliminated are cut out.

The number of incomplete rows will determine the slope of the inferior extremity. The slope of the superior extremity will be determined the same way, but the knitting sequence will be reversed. Regardless of the chosen variant, the number of rows knitted in the beginning zone is calculated with relation (1):

$$N_r = \frac{L}{B} \tag{1}$$

Where:

N_r - number of rows for the beginning and ending zones;

L - height of the beginning or ending zone, mm;

B - stitch height, mm.

The height of the beginning/ending zone is determined in the design stage, according to the specific dimensions of the wing; in this case 30 mm for the beginning zone and 25 mm for the ending zone. The calculated value is used to determine the groups of needles that will pass successively from one evolution to the other, or will successively start to work (2).

$$l_{group} = \frac{N_{needles}}{N_r} \tag{2}$$

Where:

l_{group} - width of a group of needles;

$N_{needles}$ - total number of needles working in each bed;

N_r - number of rows in the beginning/ending zone.

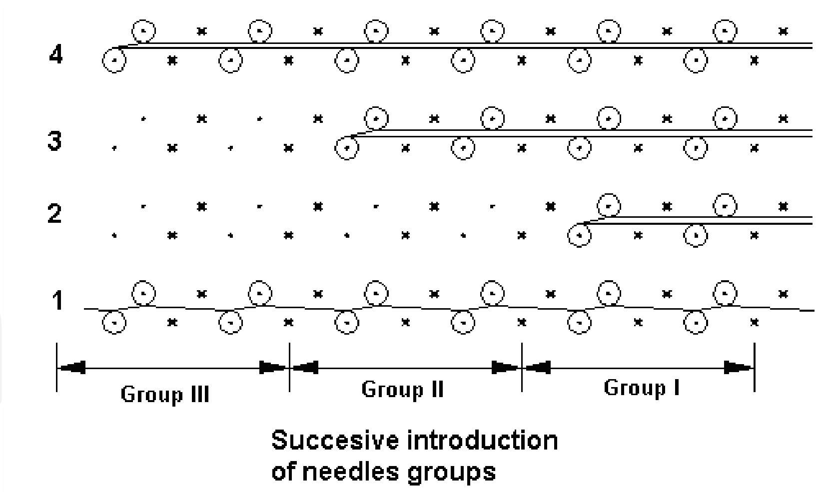


Fig. 36. Knitting sequence for the beginning zone

The inner walls of the preform

The inner walls of the preform are produced as single connecting layers of the sandwich fabric. The layer length is 80 mm, respectively 64 mm. In order to satisfy the required 5 mm thickness for the inner walls, two successive connecting layers with the same length will be knitted. After the introduction of the resin the two neighbouring connecting layers will generate an inner wall. Apart from knitting connecting layers of such high length, the production of two layers one after the other represented another problem.

During the knitting of the single connecting layer, some rows of the outer fabric are produced on the opposite bed in order to reduce the tension generated by the long period in which the needles making the outer independent fabrics miss. These supplementary rows must be taken into consideration when calculating the number of rows between the two connecting layers so that they are horizontal.

Presentation of the preform made of glass fibre

The general aspect of the preform is presented in Fig. 37. The beginning and ending zones of the outer fabrics can be observed, as well as the zones where the connecting layers were produced (see Fig. 38). One connecting zone is encircled in Fig.37.

Fig. 37. Preform with jersey evolution on selected needles

Fig. 38. Preform with jersey evolution on selected needles and fleece in-lays

The successive connecting layers are exemplified in Fig. 39 where the preform is presented in cross section, showing the two connecting layers of 80 mm length.

Fig. 39. Connection layers – cross section view and aspect of the first connection layer

Production of a supplementary exterior layer for the wing

In order to increase the fabric compactness, as well as to improve the mechanical behaviour of the preform, a supplementary exterior layer is added, covering the preform. The tubular fabric is knitted perpendicularly in relation to the direction used to knit the preform (see Fig. 40).

The fabric dimensions correspond to the ones presented in Fig. 32. The conical shape is obtained with successive, symmetrical narrowing. The tubular fabric is closed, giving a rounding effect in N_1 and N_2 zones. The closing can be done using the bind-off technique, though it is preferably to avoid its use for fabrics made of glass fabric. The repeated transfers lead to a significant amount of broken filaments, affecting the mechanical behaviour and even destroying the stitches during the introduction of the fabrics in/on the moulds before the RTM process.

Considering that there are no restrictions regarding the structure and its tensioning, the evolution chosen for the tubular fabric can be jersey, 1x1 jersey or even jersey fleece (see Fig. 41).

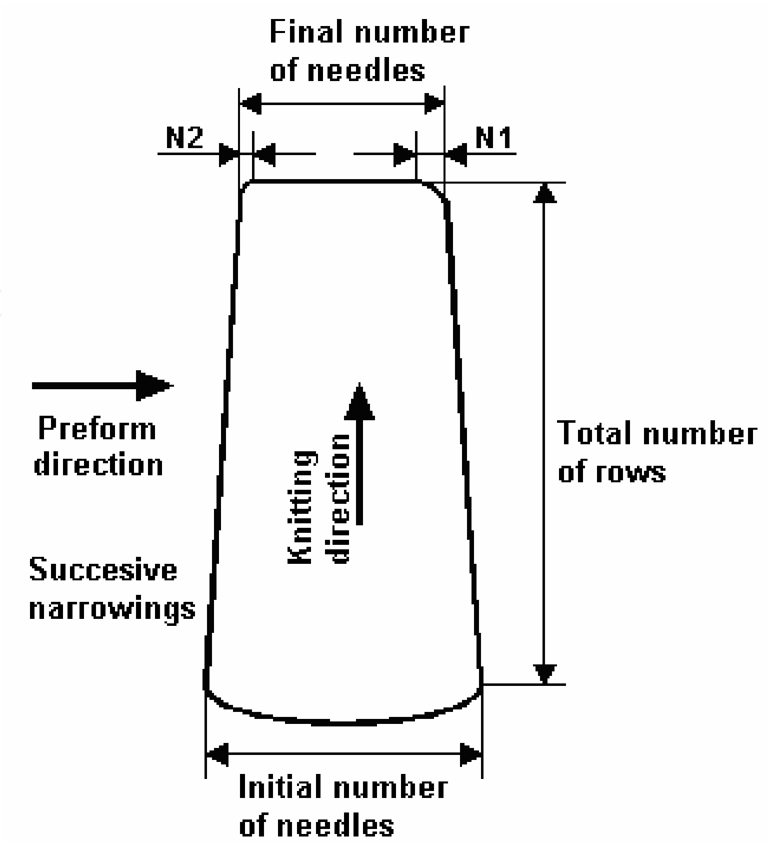


Fig. 40. Production of the supplementary layer

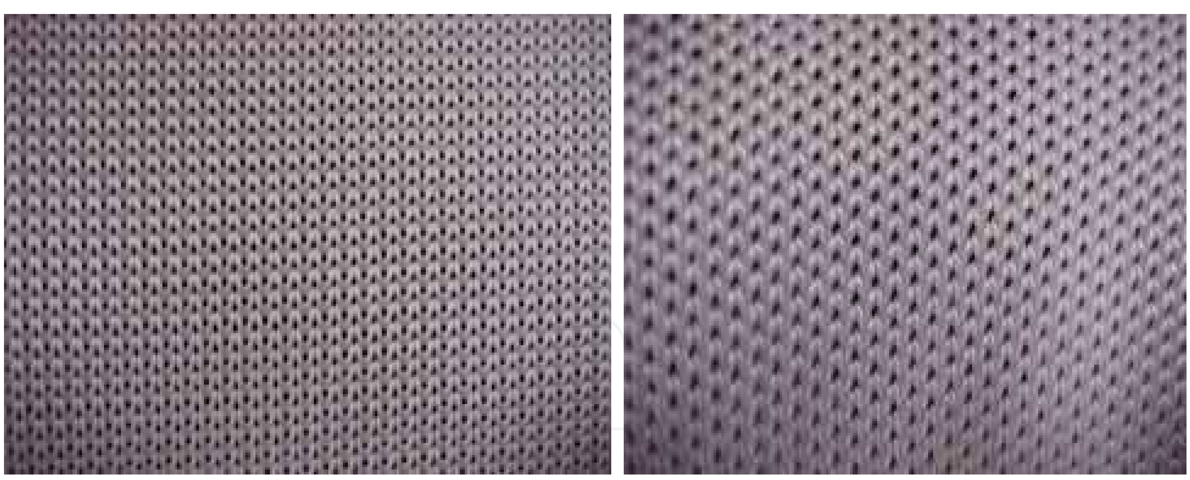


Fig. 41. Front aspect of a jersey and 1x1 miss jersey fabrics made with glass fibre count 408 tex

Production of a glider wing made of composite material using a knitted preform

The composite material glider wing was produced using an injection process RTM (Nicolau et al., 2002). The resin used was unsaturated polyester orthophtalic resin, S226E (Neste), characterised by reduced viscosity, 150 mPa·s. The pre-acceleration was obtained with a 0.15% solution of cobalt 6%. The catalyst used was Trigonox TX 44B. This recipe formula avoids resin curing during the injection process.

Moulds production

The complexity of the preform shape required exterior and interior moulds that would generate the desired shape for the composite. The exterior mould (see Fig. 42) is made of a composite material reinforced with two layers of glass fibre matt. The three interior moulds (Fig. 43) that are to be introduced in the preform, are produced with polyurethane foam and have a protective layer.

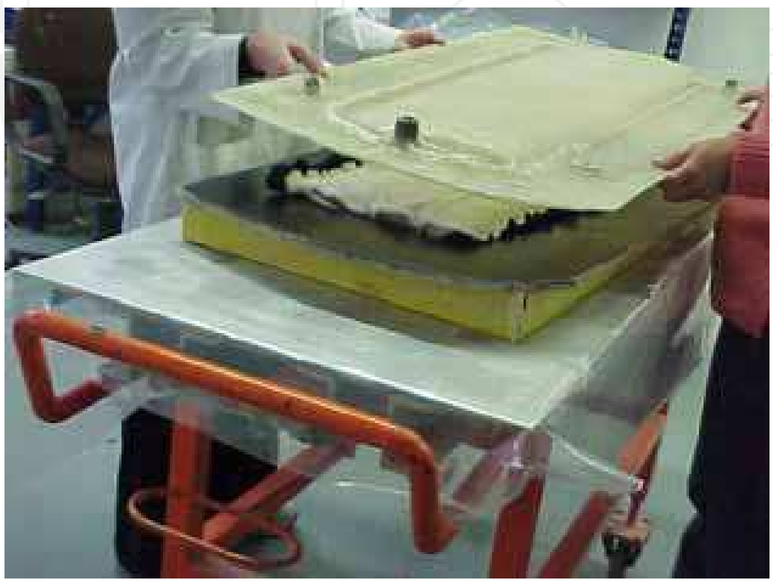


Fig. 42. Exterior mould – inferior and superior components

Fig. 43. Internal moulds – front view

Description of the RTM process

The injection process included the following stages (Nicolau et al., 2002):

- mould cleaning and application of the separation liquid;

- introduction of the interior moulds in the preform (Fig. 44) and covering with the supplementary tubular fabric;
- positioning in the exterior mould;
- mould vacuum closing;
- connecting the mould to the devices for resin injection and vacuum;
- vacuum formation inside the mould;
- resin preparation and catalyst introduction inside the bowl under 1 bar pressure;
- starting the injection process (Fig. 45).

Fig. 44. Introduction of the interior moulds in the preform

Fig. 45. Resin injection process

The polyester resin was injected inside the exterior mould at low pressure ($1{,}5 \cdot 10^5$ Pa) using the vacuum device. The injection process took approximately 30 minutes. After injection the composite material was subjected to a thermal treatment in order to complete the curing process. The composite wing is presented in Figure 46.

Fig. 46. Composite wing – aspect before and after resin injection

5. Conclusions

Knitted fabrics are well used in the field of technical textiles, including composite materials with plastic matrix. As composite reinforcement, knitted fabrics have some negative points with regard to their mechanical behaviour, but this can be improved through structure (especially the use of in-laid yarns) and structural parameters.

Other issues concern the knittability of high performance fibres (volume of fibre damage during processing) and there are ways of limiting the filament breaking phenomenon – the modification of knitting elements, lower yarn tension, etc. The study presented in this chapter identifies as main cause of destruction the rob-back stage in the knitting process, when the yarns are pulled over the trick plate under high tension. The best approach to knitting high performance fibres seams to be a case by case approach, when the knitting conditions can be determined in order to obtain good quality fabrics.

Both weft and warp knitting technologies can be used to produce composite reinforcement. Warp knitting is best suited for structures with in-laid straight yarns (multiaxial fabrics), while weft knitting allows obtaining fabrics with three dimensional architecture, used as preforms for advanced composite materials. The examples of 3D knitted fabrics presented in this chapter illustrate the idea that knitting is a viable option when considering the production of complex shapes. Further studies should explore diversification possibilities. Other directions for future development are: the design of knitted fabric in relation to 3D bodies, the simulation of fabric spatial geometry and properties prediction.

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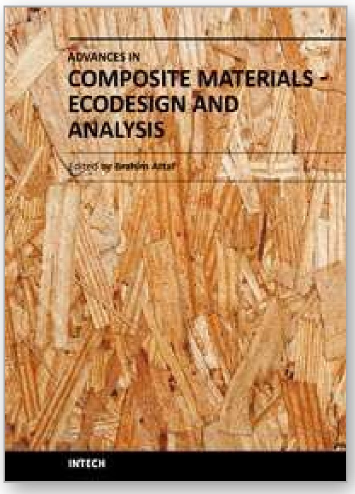

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