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COMPLEX TEXTILE STRUCTURES AS REINFORCEMENT FOR ADVANCED COMPOSITE MATERIALS

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Abstract: *Fiber reinforced composites were primary developed for aerospace and defense applications. High performance materials were designed and obtained exploiting the fibers high strength-to-weight ratio. The well known complex textile structures used as reinforcements for advanced composites are 2D and 3D woven fabrics and nonwoven fiber mats, but the knitted fabrics (weft knitted structures, as well as warp knitted) are of high interest in last decades due to their properties and development potential. There are three main types of 3D knitted structures: multiaxial fabrics (multilayer), knitted fabrics with spatial geometry (spatial fashioned) and sandwich/spacer fabrics. Their characteristics and applications are summarized herein.*

Keywords: *fiber reinforced composites, 3D knitted structures, aerospace applications*

1. INTRODUCTION

The history of textiles can be traced back to the prehistoric times. Current applications of textiles have crossed many barriers and reached limits beyond expectations. Fields like sports and leisure, healthcare and wellness, energy generation and storage, electronics and IT, automotive and aerospace, just to give a few examples, are using hi-tech textile reinforced composite materials. Fiber reinforced composites were primary developed for aerospace and defense applications. In these industries, high performance considerations overbalance cost efficiency criteria. High performance materials were, therefore, designed and obtained exploiting the fibers high strength-to-weight ratio. Textile reinforced composites proved to be competitive materials due to certain advantages, in addition to their strength (given by the fiber/yarn structure) and unity and ability to transmit strains (ensured by the polymeric matrix):

- controlled anisotropy (due to textile reinforcement) - their structure can be designed so that fibers are oriented in preferential directions, depending on the maximum strain;
- textile reinforcements allow to obtain composites with a better weight-to-strength ratio in comparison with steel and other classic materials used for such applications;
- textiles maintain their integrity and behavior under extreme conditions: they are not susceptible to corrosion in outdoor applications, display dimensional stability under significant

temperature gradient, are not sensitive to electromagnetic fields;

- these composites have an improved fatigue resistance.

Advanced composites based on technical textiles can be found in many industrial applications as storage and transport structures (tanks, pipes, hoses, etc.) [1]. The automotive industry uses them for car frames and other automobile parts (manifold, wheels), whilst in aeronautics composites developed from the 1st level to 2nd level applications (it refers to structural elements) [2] and the future aircraft trend is to build them using exclusively composites. One application of great interest nowadays is the energy production management, especially when it comes to wind energy (wind mills) [3]. Sport equipment industry is employing high amounts of textile reinforced composites in the production of sporting goods and protective equipment (helmets, etc.). An interesting application is in civil buildings, as walls reinforcement, aiming to obtain strengthened structures with reduced thickness and, subsequently, low production costs [4].

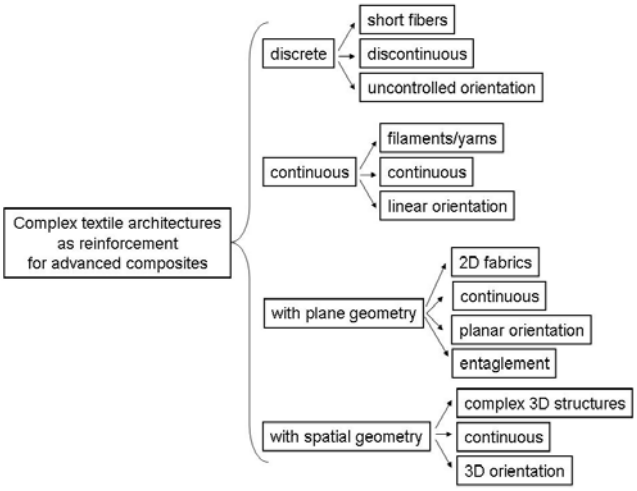
2. COMPLEX TEXTILE STRUCTURES

2.1 Types of complex textile structures.

An introduction in complex textile structures used as reinforcement in advanced composites has to take into account two basic criteria: (1) textiles geometry (structure) and (2) the processing [5].

Considering the significant dimension of the textile material and its specific geometry [6], it is possible to define such structures as: unidimensional (non-axial – roving yarns), bidimensional (monoaxial – chopped strand mats; non-axial – sheets; biaxial – plain weave; triaxial – triaxial weave; multiaxial) and tridimensional (liniar element – 3D solid braiding, multiple weave, triaxial and multiaxial 3D weave; plane element – laminates, beams, honeycombs). In this classification, the preset fibers directions used in the material structure was also allowed for.

Depending on their architecture [7], textile reinforcements can be assorted into 4 groups, as follows: discrete, continuous, with plane and spatial geometry, as presented in Scheme 1. The textile component may be represented by short fibers, filaments or yarns, fabrics or complex structures, continuous or not, with (un)controlled orientation.



Scheme 1. Classification of textile reinforcements according to their architecture

In terms of technology, all specific processes from textile industries may be used to produce complex structures, but, due to their chacracteristics and the material geometry that results, they lead to different behavior and recommend materials for various applications. The main production processes employed in textile reinforcements are weaving, braiding, knitting and nonwovens production. Other processes, such as filament winding and poltrusion, which process filaments, are also applied. The selection of a specific technological process takes into account its architectural capabilities, the material characteristics and behavior (dimensional stability, mechanic strength, drapability and formability, etc.), as well as its suitability for the composite processing and application.

2.2 Fibers used for complex textile structures. Textile reinforcements are using high performance fibers such as glass, carbon/graphite, aromatic polyamides (aramides – Kevlar), polyesters (HM/HT PES), ceramic fibers, boron and silicon carbide fibers, etc. They have superior mechanical characteristics, as presented in Table 1, so that can meet the specific demands of advanced composite applications. Their high bending rigidity and other properties that affect the knitting process must be taken into consideration when designing a knitted structure as reinforcement for composite materials [2].

Table 1. Main characteristics of fibers used in textile reinforcements

Fiber	Relative density (g/cm^3)	Young`s modulus (GPa)	Tensile strength (GPa)
Carbon	2.0	400	2.0-2.5
Boron	2.6	400	3.4
E-glass	2.5	70	1.5-2.0
S-glass	2.6	84	4.6
Kevlar 29	1.44	60	2.7
Kevlar 49	1.45	60	2.7

Glass fibers (yarns, rovings) are the most common high performance fibers used to reinforce composite materials. They are characterized by hardness, resistance to chemical agents, stability and inertness, low weight and processability [4]. There are more types of glass fibers 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, used mainly in military applications; and C-glass, characterized by chemical stability and corrosion resistance. The glass fibers possess high strength, low elongation, high bending rigidity and brittleness. It was shown that glass fibers can resist when bent around the needle hook and, therefore, can be processed through knitting [8,9]. Due to their brittleness and low resistance to friction, the glass yarns are easily damaged, thus affecting the knitting process and, subsequently, the real strength of the reinforcement. Therefore, it is required to identify optimal processing parameters prior to knitting glass fibers. The fabric density and the amount of damaged fibers strongly affect the performance of the final composite. So, a high fiber fraction volume is mandatory for advanced composite materials.

2.3 Knitted fabrics. The most used composite reinforcements are 2D and 3D woven fabrics and nonwoven fiber materials, but the knitted fabrics (weft knitted structures, as well as warp knitted) are of high interest in last decades due to their properties and development potential. The main advantages of knitted fabrics for composite reinforcement are:

- ➢ they allow knitted fabrics with complex tridimensional shapes;
- ➢ it is possible to improve the fabric handling and plastic injection during composite processing;
- ➢ acceptable processability of high performance fibers (glass, aramid, PES HT or HM);
- ➢ short intervals of production;
- ➢ controlled anisotropy (yarn in-laid under preferential angles).

Compared to other textiles (woven, braiding, non-crimp materials), knitted fabrics display lower values for in-plane strength and stiffness. Another issue limiting their use is the low volume fraction, due to their specific geometry of knitted stitches, characterized by areas without yarns.

Mechanical properties are controlled by fabric structure and characteristics, yarn properties and process parameters. Using float stitches and in-laid straight yarns placed under certain angles it is possible to improve material characteristics by controlling its structure. Stitch density also affects the tensile behavior and fabric stiffness. Yarns influence the material behavior, their properties being transferred to the final structure. The bending strength and rigidity of the knitted fabrics essentially depend on the process specific parameters, considering that high performance fibers are rigid and, therefore, they must be processed carefully. The use of in-laid straight yarns eliminates the problem of fiber damage and also increases the volume fraction [4].

Warp knitted fabrics (Figure 1) are resistant to runs and relatively easy to sew. Among their advantages, there are higher productivity rates than weaving, the variety of fabric constructions, large working widths and low stress rate on the yarn (that enable it for rigid fibers such as glass, aramide and carbon), etc.

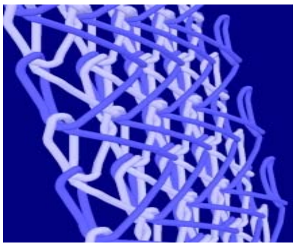


Figure 1. A warp knitted structure

Stitch-bonding is a special form of warp knitting and is commonly used for the production of composite materials and technical textiles (Figure 2). It is an efficient process and one of the most modern ways to create textiles reinforced composite materials for industrial use. The advantages of the stitch-bonding process include high transverse stability and resistance to tearing, low stretch that enables an enhanced transfer of yarn properties, as well as high productivity rate and the scope it offers for functional design of textiles, such as fiber-reinforced plastics [10].

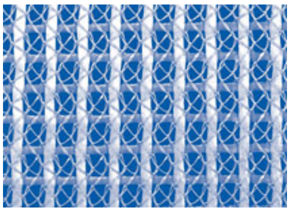


Figure 2. Illustration of a stitch-bonded fabric

Weft knitting is commonly used for garments, such as socks or T-shirts, because the resulting materials may fit shapes. This structure (Figure 3) makes the material elastic whatever the fiber.

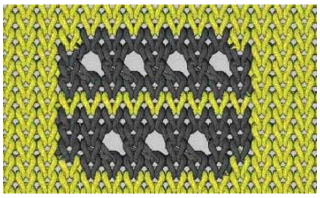


Figure 3. Example of a carbon-Kevlar weft-knitted structure

This feature may be of great use in order to produce composite reinforcements for different aircraft parts, such as cabin equipment. Still, these techniques have some disadvantages: (1) there are almost no finite element models to predict the behavior of the knitted materials; (2) the elasticity of the preform does not allow the manufacturing of high-performance parts. Weft knits are produced with circular and flat machines and most types of yarns can be used, it is even possible to mix different yarns in various areas using the intarsia technique (for instance, it is possible to knit a Kevlar zone inside a carbon part to bring cutting resistance) [11].

3. TRIDIMENSIONAL KNITTED STRUCTURES

Knitted fabrics can easily achieve 3D architectures due to their high extensibility and formability that allow complex shapes. This is the reason why the knitted fabrics are regarded as a viable option for preforms for advanced composite materials [4].

The main advantages of the 3D knitted structures are, as follows:

- fabrics high formability due especially to their drapability;
- shapes high complexity and wide variety;
- the use of the already existing technology, without major modifications;
- good impact resistance.

Specific properties of these textile structures are given by their complexity. Knitted 3D performs are currently under study and the development of these fabrics, yet at laboratory stage, still needs a significant input from the R&D community in terms of improving their characteristics, developing up-graded production protocols (for example, impregnation with resin yields in an uneven behavior of the composite due to fibers migration in stitches), as well as prediction models.

There are three main types of 3D knitted structures: multiaxial fabrics (multilayer), knitted fabrics with spatial geometry (spatial fashioned) and sandwich/spacer fabrics.

3.1 Multiaxial fabrics (multilayer). The multiaxial fabrics are characterized by multiple layers of yarns arranged under certain angles that are finally assembled into knitted fabrics (Figure 4). These fabrics are produced on special warp knitting machines using glass or carbon fibers for layers.

The different layers in the multiaxial warp knitted fabrics are independent and the yarns are fed under preset angles corresponding to the directions requiring higher strength during use, criterion imposed by the application.

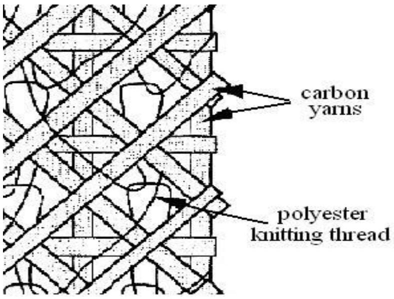


Figure 4. Typical multiaxial knitted structure (carbon and polyester yarns)

The layers are connected within the knitted fabric, by the means of pillars or tricot stitches. By using warp knitting techniques in conjunction with fiber placement concepts, multilayer structures containing straight and relatively uncrimped fibers stacked in the required orientations can be produced. The warp knitting technology is best suited for this kind of structures with in-laid yarns. These fabrics have excellent dimensional stability and outstanding in-plane shear resistance in all directions, show higher elastic modulus compared to woven fabrics, and their tear strength is higher than that of wovens (probably due to the shifting of yarn layers under force and bunch together to resist tearing). Multiaxial fabrics are used mainly as composites reinforcement (HM or HT polymer filaments, such as polyester, nylon and PEEK, and glass, aramid or carbon fibers/yarns) [12,13].

3.2 Spatial fashioned knitted fabrics. The spatial fashioning of the knitted fabrics is based on the need to produce fabrics with complex shapes that are similar to the final product shape. Even if a certain degree of spatial geometry can be obtained by using modules of structures with different patterns or by dynamic stitch length, this technique is the only one that allows textile component parts of great variety in shape and diverse degrees of complexity [4]. Spatial fashioned knitting (also known as "flechage") is based on two different types of knitting courses, on all working needles and on a variable number of needles, determining zones with different geometry. Areas with the highest amount of stitches will have, in the end, a spatial geometry (Figure 5A and B) [14].

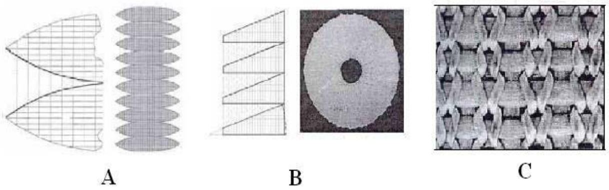


Figure 5. Spatial fashioned knitted fabrics: A – sphere; B – disc; C - jersey fabric with warp and weft yarns inserted in the structure

One issue connected to the use of preforms made of fashioned fabrics refers to their relatively low strength which can be improved by inserting both warp and weft yarns within the structure (Figure 5C). Apart from increasing the fabric strength, this technique also improves the volume fraction of the material, with beneficial effects on the properties of the final composites.

3.3 Sandwich/spacer fabrics. A sandwich or a spacer structure is a 3D assembly made of two separate fabrics, interconnected through simple yarns or knitted layers. The fabric thickness is determined by length of the connecting yarns/layers [4].

When produced on warp machines, these fabrics are known as spacers and thickness depends on the distance between two consecutive layers (spacer distance). An interesting application of such spacer fabrics are the textile reinforced concrete panels is used in buildings.

In the case of weft knitting, the fabrics are known as sandwich structures. The connection can be generated through yarns fed on both beds or by knitted layers. In the first case, there are limitations in terms of shape complexity and fabric thickness. The second approach implies to separately knit the two beds and, at a certain point, to stop and knit the connection layer only on selected needles [4]. Examples are given in Figure 6.

(a)

(b)

Figure 6. Spacer fabric made of glass fibers (a) and a sandwich structure (b)

3. CONCLUSION

By combining textile processing techniques with advanced materials characterization methods and prediction models, it it possible nowadays to obtain advanced composites with outstanding properties using complex textile structures as reinforcement.

Knitted fabrics are well known for their applications in the field of technical textiles, including composite materials with polymer matrices. Both weft and warp knitting technologies can be used to produce such reinforcements. Warp knitted fabrics are best suited for structures with in-laid straight yarns (multiaxial fabrics), whilst weft knitted ones allow structures with tridimensional architecture, used as preforms for advanced composite materials. The complex 3D textile systems are being used mostly in defense and aerospace applications (for example, glider wings), where they can effectively replace conventional materials.

A better understanding of the mechanism of fibers reinforcement in composite materials enables the design and production of new high performance textile-based composites for a wide range of applications. Technology optimization will yield in reduced production costs, while geometrical modeling and predictive calculations of the physical and structural properties of textile complex structures will result in preforms with tailored properties.

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