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Textile Reinforced Structural Composites for Advanced Applications

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ABSTRACT: The subject of composite materials reinforced with textile fabrics is a multifaceted domain. While explaining these materials, it becomes essential to consider their mechanical properties, with a specific focus on their ability to withstand impacts, as many applications involve dynamic stresses. Initially, fiber-reinforced composites found their primary purpose in aerospace and defense applications, leveraging the impressive strength-to-weight ratio of the fibers. While 2D and 3D woven fabrics, along with nonwoven fiber mats, have long been recognized as intricate textile structures for advanced composites, knitted fabrics, encompassing weft and warp knitted structures, have garnered substantial attention in recent decades due to their unique attributes and growth potential. Among 3D knitted structures, three primary types stand out: multiaxial fabrics with multiple layers, knitted fabrics featuring spatial geometries, and sandwich/spacer fabrics. This abstract provides a comprehensive overview of their characteristics and applications.

KEYWORDS: Fiber reinforced composites, 3D knitted structures, Aerospace applications

I. INTRODUCTION

The origins of textiles can be traced back to prehistoric times, and their contemporary applications have transcended boundaries, pushing the limits beyond all expectations. Fields such as sports and leisure, healthcare and wellness, energy generation and storage, electronics and information technology, automotive, and aerospace, to name just a few, now leverage advanced textile-reinforced composite materials. Initially, fiber-reinforced composites were primarily developed for the demanding needs of the aerospace and defense sectors, where high performance consistently took precedence over cost efficiency considerations. These materials were meticulously designed to harness the exceptional strength-to-weight ratio. Textile-reinforced composites, in addition to their inherent strength derived from the fiber and yarn structure, and their ability to efficiently transmit strains facilitated by the polymeric matrix, have demonstrated competitive advantages:

- 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, incorporating technical textiles, have found wide-ranging utility in diverse industrial sectors. In applications such as storage and transportation structures (e.g., tanks, pipes, hoses) [1], these materials have become indispensable. The automotive industry has adopted them for constructing car frames and various automobile components, including manifolds and wheels. In aeronautics, composites have evolved from first-level to second-level applications, predominantly in structural elements [2]. A noteworthy trend in the aeronautical sector is the exclusive use of composites in crafting future aircraft. Presently, one of the most compelling areas of interest lies in the management of energy production, particularly in the context of wind energy (wind turbines) [3]. The sports equipment industry is making extensive use of textile-reinforced composites for the fabrication of sporting goods and protective gear, such as helmets. Additionally, an intriguing application has emerged in civil construction, where these composites reinforce walls to fortify structures while reducing thickness and, consequently, production costs [4].

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II. COMPLEX TEXTILE STRUCTURES

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, composites as follows: discrete, continuous, with plane and spatial geometry, as presented in Figure 1. The textile component may be represented by short fibers, filaments or yarns, fabrics or complex structures, continuous or not, with (un)controlled orientation.

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].

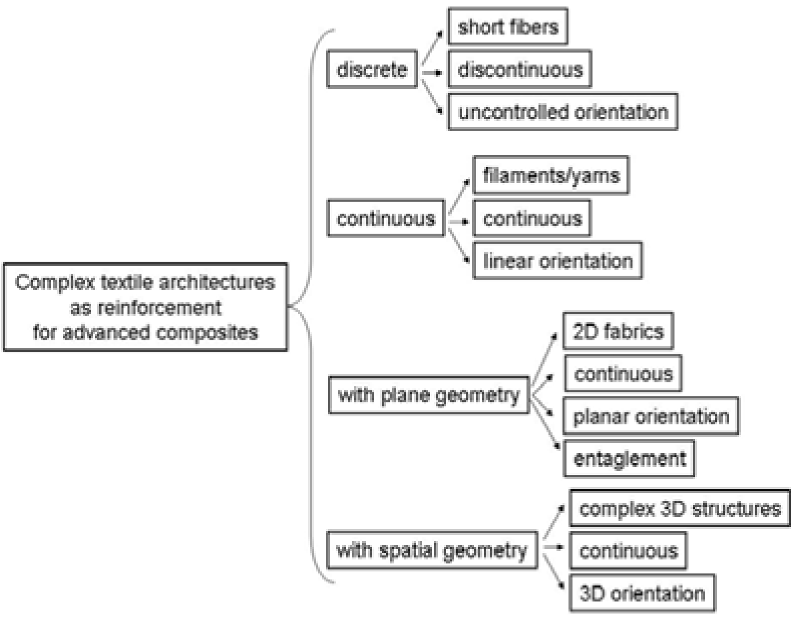

Figure 1. Classification of textile reinforcements according to their architecture

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 non- wovens 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.

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].

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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.

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 process ability 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.

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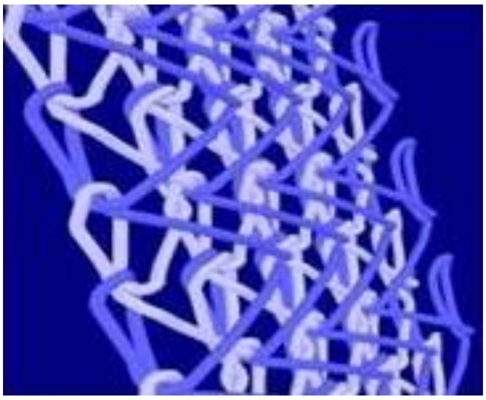

Figure 2. A warp knitted structure

Stitch-bonding is a special form of warp knitting and is commonly used for the production of composite materials and technical textiles (Figure 3). 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].

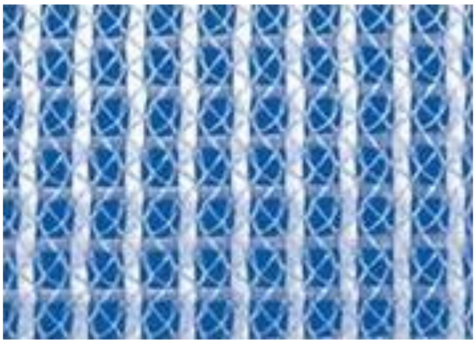

Figure 3. Illustration of a stitch-bonded fabric

Weft knitting is commonly used for garments, such as socks or T-shirts, because the resulting materials may fit shapes. This structure (Figure 4) makes the material elastic whatever the fiber.

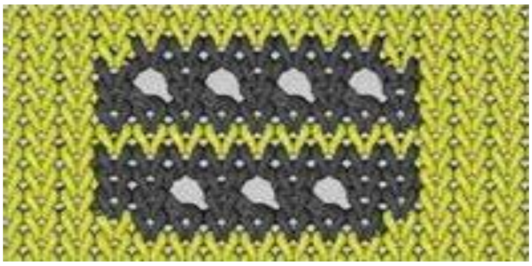

Figure 4. Example of a carbon-Kevlar weft-knitted structure

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].

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III. 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:

- Fabric's high formability especially due 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.

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.

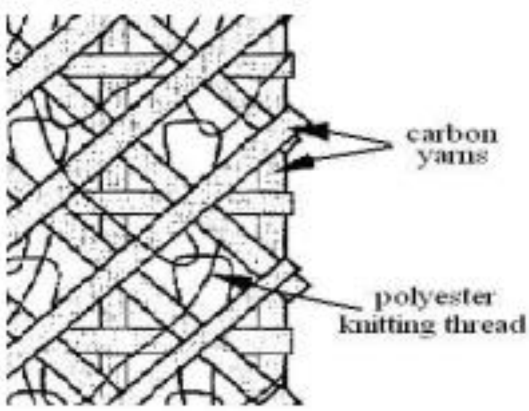

Figure 5. Typical multiaxial knitted structure (carbon and polyester yarns)

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].

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.

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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.

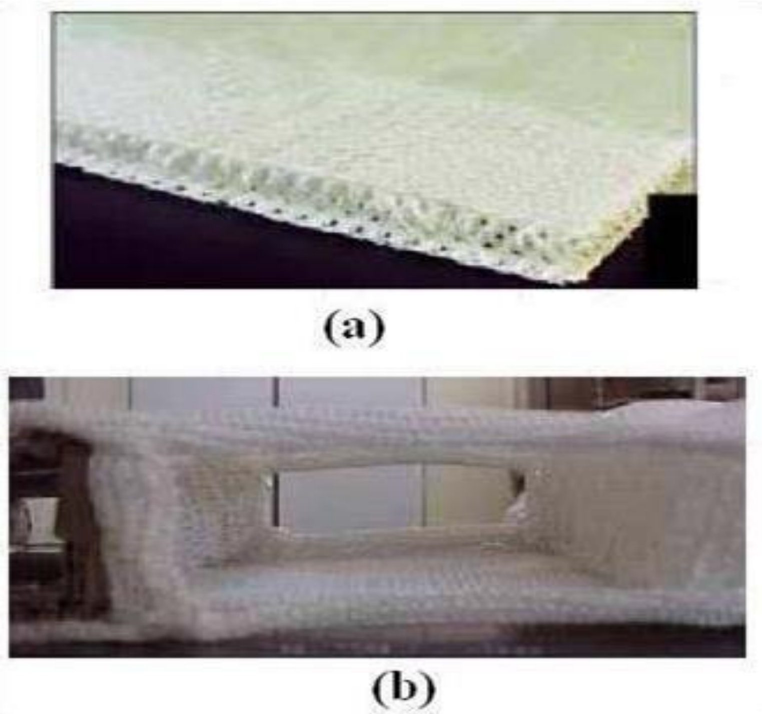

Figure 6. Spacer fabric made of glass fibers (a) and a sandwich structure (b)

IV. CONCLUSION

The fusion of textile processing techniques, advanced materials characterization methods, and predictive modeling has opened up new frontiers in the creation of advanced composites boasting exceptional properties, utilizing complex textile structures as their reinforcement. Knitted fabrics, with their well-established presence in the field of technical textiles, have proven invaluable in composite materials featuring polymer matrices. Both warp and weft knitting technologies serve unique purposes, with warp knitted fabrics being optimal for in-laid straight yarns (multiaxial fabrics) and weft knitted fabrics allowing for complex three-dimensional architectures, essential as preforms for cutting-edge composite materials. These complex 3D textile systems have found prominent applications in defense and aerospace sectors.

A deeper understanding of the mechanisms by which fibers reinforce composite materials is the key to designing and manufacturing novel high-performance textile-based composites, applicable across a wide spectrum of industries. The optimization of technology promises reduced production costs, while the integration of geometrical modeling and predictive calculations regarding the physical and structural properties of complex textile structures results in preforms tailored to specific requirements.

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