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CHARACTERISATION OF CARBON TAILORED FIBRE PLACEMENT REINFORCED COMPOSITES

DOMENECH-PASTOR Jorge[1], GONGA Eloi[1], CAMPOS Juan[1], DIAZ-GARCÍA Pablo[2], GARCIA Daniel[3]

[1] Asociación de Investigación de la Industria Textile – AITEX, Smart Textiles Research Group, Postal address, ES03801 Alcoy, Spain, E-Mail: jdomenech@aitex.es; egonga@aitex.es; jcampos@aitex.es

[2] Universitat Politècnica de València (UPV), Escuela Politécnica Superior de Alcoy, Ingeniería Textil y Papelera (DITEXPA), Plaza Ferrándiz y Carbonell 1, 03801, Alcoy, Spain, E-Mail: pdiazga@txp.upv.es

[3] Universitat Politècnica de València (UPV), Escuela Politécnica Superior de Alcoy, Instituto de Tecnología de Materiales (ITM), Plaza Ferrándiz y Carbonell 1, 03801, Alcoy, Spain, E-Mail: dagarga4@epsa.upv.es

Corresponding author: Domenech-Pastor, Jorge, E-mail: jdomenech@aitex.es

Abstract: *It is known that carbon reinforced composites are stronger at the orientation of the fibers. However, plain woven fabrics (PWF) are limited in terms of fibre orientation to 0º and 90º, except axial woven fabrics which could guide and orient fibres in some angles e.g.: 30º 45º 60º, etc. In this sense, material isotropy is increased by overlapping fabrics with 2D and 3D fabrics structures. For this reason, it is interesting to consider the development of customized composites with fibers in curved orientations that adapt to the design and shape of the final product, in order to improve the mechanical properties and behaviour of a piece. Orienting fibres in multiple directions offer a new perception to study the anisotropy of carbon fibre reinforced polymers.*

Tailored Fibre Placement (TFP) used in embroidery can produce textiles with curvilinear designs and align these reinforcing fibres in accordance with the product design, shape and geometry. TFP allows the adaptation of fibres to holes and locate the fibres in around the edge of the hole. This demonstrate the importance of stress and loads and the orientation of the fibres.

This study characterises and analyses the mechanical properties of carbon tailored fibre placement composites under tensile vertical efforts of a curvilinear design in comparison with unidirectional fibre placement composites.

Key words: *embroidery, polymers, anisotropy, textile, tensile, Resin Transfer Molding*

1. INTRODUCTION

Composite materials can satisfy multiple needs as they are very diverse in nature. The variety of options available such as type of fiber, resin, tools, processes and finishes allow to manufacture almost any composite part for almost any application. Combining these materials with the tremendous strength, rigidity, durability, and light weight that composites offer, is one of the reasons why in the last decades, the interest in polymeric composites is replacing other materiales such metal, wood and ceramics [1], [2].

Fiber reinforced polymeric composites are being used due to their high strength and low weight advantages in many industries such as automotive and aerospace [3]. However, one of the main problems using fiber reinforced polymeric composites is that the carbon fibre fabrics dispose the fibers perpendicularly and unidirectionally, and when the pieces show different shapes, to obtain the right properties it is necessary to overlap several reinforcing fabrics.

In the composite industry, generally glass and carbon fibres are most widely used materials because of their high strength to weight ratio [4]. Nevertheless, carbon fibres are the predominant high strength and modulus reinforcement used in the fabrication of high-performance polymer-matrix composites. Carbon fibres typically contain more than 90 weight percentage of carbon and have remarkable properties. In general, they include high tensile strength (up to 7 GPa), good compressive strength (up to 3 GPa), high tensile modulus (200 up to 900 GPa), low density (1.75 up to 2.18 g/cm3), good temperature resistance, low thermal expansion, good electrical and thermal conductivity, and chemical resistance [5], [6]. In this sense, the combination of carbon fiber with polyester resin is something that has already been widely studied in the field of engineering and materials. Traditionally, these composites have been reinforced with plain woven fabrics of carbon fibers. These woven fabrics are limited in terms of the of fibers aligment since they can only vary the ligament causing visual or ornamental effects; and the only way to modify the orientation of the fibers is through axial fabrics that allow the fibers to be oriented at certain angles of inclination, but all of them in straight lines and unidirectional, without curves [7] [8]. This overlapping increases the time of processing the composite and it depends on the experience of the worker to dispose the reinforcing fabrics. Carbon reinforced composites are stronger at the orientation of the fibers [9]. For this reason, there are several studies of double and multiple fabrics made with axial fabrics that have managed to improve the isotropic behavior of the composite by overlapping reinforcing fabrics [10] [11]. The improvement in mechanical properties and behaviour by combining multiple fabrics with various fiber orientations and by aligning them in the stress direction is evident. However, it entails a high fiber expense and consequently a higher cost of the resulting composite. In this way, it seems evident that plain woven fabrics and traditional weaving technology is insufficient to develop high performance composites, with very concrete and specific applications, since the orientation of the fibers is limited to one direction and certain angles.

These are some of the most common weaving structures. All of them agree that they do not have an arrangement of fibers with curved shapes, arches and that in order to achieve a structure with greater isotropy, layers of fabrics are overlaped on each other. This implies that to achieve a certain behavior of the composite in a certain direction, it is necessary to overlap several fabrics, increasing the amount of fiber and the cost of the composite. This do not happen when using embroidery technology TFP (Tailored Fibre Placement), since it allows to manufacture composite with variable axial geometry, achieving laminar structures with fibers aligned in multiple directions in order to achieve the desired mechanical performance [12].

2. EXPERIMENTAL

2.1 Objetives

This study aims, without using plain fabrics, to evaluate the behaviour under vertical tensile strength efforts of tailored fibre placement reinforced polimers, produced by embroidery technology in two different structures. One with fibres oriented in horizontal and vertical direction (simulating woven fabrics) named as PWF1 and another with fibres with curvilienear orientations named TFP1.

2.1 Materials

The carbon fibre used to develop the composite samples was model TC-35 6K multifilament of 400TEX from manufacturer Tairyfil. This carbon fibre was embroidered on a polypropylene nonwoven substrate of 0.25mm thickness and 30g/m2. The placement of the carbon yarns on the non-woven substrate is done covering the entire surface of the substrate, either vertically and horizontally in the first example (PWF1) or vertically and curvilinear-waved-horizontally in the second (TFP1). The weight per square meter of the products obtained does not present significant differences. The resulting PWF1 embroidered substrate have a weight per square meter of 491,52g/m^2 and the TFP1 479,86g/m^2.

As matrix of the composite it has been used a polyester DCPD (DiCycloPentadiene Resin) resin, RESICHIM 209 produced by Gazechim.

2.1 Equipment

The equipment necessary for the formation of the composite was, on the one hand, the RTM (Resin Transfer Moulding) equipment assisted by vaccumm to produce the composite; model CIJECT TWO provided by Composites Integration. On the other hand, an embroidery machine has been used to place carbon fibre on a PES nonwoven substrate. Tailored fibre placement was done with an embroidery machine from ZSK manufacturer, model SGZA 0109-825. In order to impregnate the reinforcing fabric (500x500mm) with the PES resin, the vacuum pump was used.

To cut the samples according to UNE-EN ISO 527-1:2019 a CNC (Computer Numerical Control) machine model 200W Mini CNC 3040 3 axis provided by ZHONG HUA JIANG was used.

For the tensile strength test, a universal testing machine, from the manufacturer IBERTEST, model ELIB-50-W, has been used. Samples with a section of 10x1.2mm were used.

2.2 Processes

Unlike the conventional approach of weaving the fibers of a composite in a perpendicular layout and then cutting the fabric to the required shape, the TFP technique organizes the fibers by aligning them exactly where they are most needed for structural performance and stitching them on a base substrate. This technique offers freedom of fibre placement, allowing fibers to be positioned in the optimal directions to transport loads, ensuring stability during processing and reducing fiber waste [13], [12]. The fibre deposition technique is carried out using a fibre guider that, by means of an oscillating zig-zag movement, fixes the fiber on a textile woven or non-woven substrate. This technique also allows the use of different thermoplastic fibers combined with structural elements like glass or carbon fibers. However, in this study only carbon fibres were used during the embroidery. It should be noted that for composite development the TFP technique must be combined with a subsequent closed-molding processes such as RTM or vacuum assisted resin infusion [14].

***Fig. 1**: PWF1 embroidering process, RTM equipment and composite plate obtained*

The process called RTM (Resin Transfer Molding) is the process of manufacturing composites in a rigid closed mold composed of two parts: male and female. The dry textile reinforcement is introduced inside the mold and it is hermetically closed so that there is no pressure loss. The resin is injected from a lateral of the mold, directly into the reinforcing fiber package and the pressure generated by the injection causes the mold to fill. The mold has outlets at the furthest points from the injection hole, allowing the air inside the mold to escape and allow the resin to take its place, impregnate the reinforcing fibres and cover the whole surface [15], [16].

The RTM mold closure is mechanically assisted with screws and bolts. On the other hand, the mold must be rigid so as not to deform and resist the forces generated by the injection process. The mold is made of aluminium and has a sensor to control the temperature, which allows to accelerate the curing of the resin and reduce the cycle time. The injection is made from a single lateral point and the resin flows through a distribution chanel around the perimeter of the mold. In a central point of the mold is located a vacuum channel to evacuate the excess resin to the catch pot. In the case estudied, it was used a DCPD resin with low styrene content which prevent workers to be in contact with VOC (volatile organic compounds) from the resin. But in other occasions, the RTM process also allows resin loaded with low shrinkage additives to be used to achieve an excellent surface appearance of the finished part [17], [18].

2.3 Results

Two textiles obtained by embroidery processes were tested under vertical tensile strength efforts, because the samples were produced to be tested in that direction. Two designs of fibre placement where studied, one with yarns in vertical and horizontal (PWF1) and another with yarns oriented in vertical direction and curvilinear (TFP1) (Fig.2). Five samples from each design were tested under vertical tensile strength efforts. For the calculation of the tensile values and graphical representation only the 3 most coherent values were considered for this study.

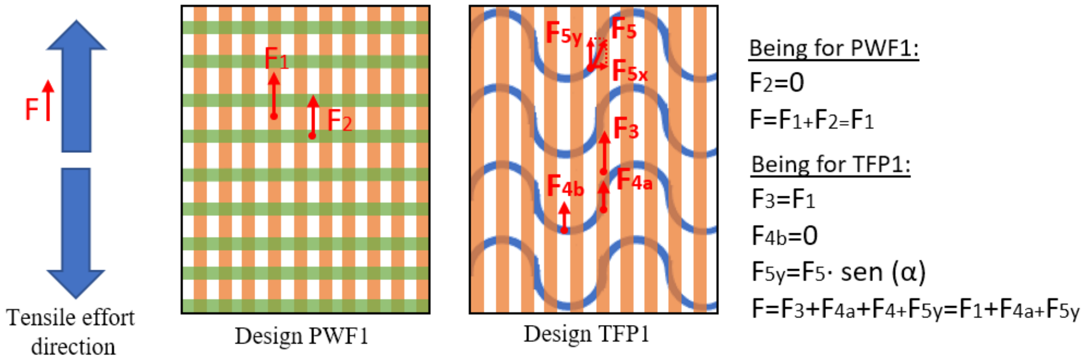

Fig. 2*: Design scheme of reinforce fibres in samples PWF1 and TFP1, and effort applied directions. F1 and F3 applied in orange coloured fibre, F2 applied in green fibres and F4 and F5 applied to blue fibres. Although gaps between threads are seen in the scheme, they do not exist in the sample. The threads are all juxtaposed.*

From the results obtained (Table 1) it is observed that curvilinear designs (TFP1) improve tensile properties as there is an increase in tensile strength from 125.7 MPa for the PWF1 sample to 140.7 MPa for the TFP1 sample, which represents an increase of 11.9%. Regarding the Young Module, a notable decrease can be observed with respect to the reference sample PWF1, going from 6267 MPa to 4371 MPa, which represents a decrease of 30.2%. Finally, regarding elongation, it can be seen how the TFP1 design shows a greater elongation with respect to the reference sample, producing an increase of 39.62%, going from 3.5 for the PWF1 sample to 4.9% for the TFP1 sample.

Table 1: *Tests results*

Sample	PWF1			TFP1		
	Elastic Modulos (Mpa)	Max. Tensile strength (MPa)	Elongation (%)	Elastic Modulos (Mpa)	Max. Tensile strength (MPa)	Elongation (%)
1	5400	113,4	3,4	5400	169,6	5,7
2	6650	150,8	3,3	4214	129,5	4,0
3	6750	112,8	3,7	3500	123,1	4,9
Average	6267	125,7	3,5	4371	140,7	4,9
Standard Dev.	752	21,8	0,2	960	25,2	0,9

5. CONCLUSIONS

Tailored fibre placement embroidery technology allows to improve the behaviour of regular fibre reinforced composite, due to the possibility to align the fibres in the direction of the effort. TFP also offers freedom of designs and structures in comparison with plain oven fabrics and axial woven fabrics where only some angles are possible.

Composites with axial fibre placement like PWF1 have a good behaviour in terms of mechanical properties when efforts are in the same direction than the fibre. In contrast, they obtain bad results when the effort is applied in a different direction (e.g. perpendicular) to the fibre. On the other hand, composites with curvilinear aligned fibres obtain better results due to the superposition of forces and decomposition of loads in normal (vertical and horizontal) forces components phenomenoms along the fibres and interfase of the resin matrix ($F_3+F_{4a}+F_{5y}$). As there are always some fibres in the direction of the force effort (F). This decomposition and superposition of efforts is the reason why maximum tensile strength is higher in TFP1 than in PWF1, because the aggregated forces $F_3+F_{4a}+F_{5y}$ in TFP1 are higher than F_1 in PWF1.

In the case under study, an improvement of approximately 12% of maximum tensile strength is obtained using the same quantity of fibre in both composites and without increase costs. This increase of 12% can be considered a lot in some industrial domains and can be very important for high technique applications like automotive or aerospace industry. In addition, the TFP1 is less rigid than PWF1 and the TFP1 sample has a more elastic behaviour. Currently, within this promising new line of research, new fabric architectures manufactured by the embroidery machine are being studied with the aim of obtaining composite materials with improved mechanical properties.

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