CARBON FIBRE ALIGNMENT FOR REINFORCED COMPOSITES USING EMBROIDERY TECHNOLOGY

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Abstract: Composites are materials formed by the combination of two or more components that acquire better properties than the ones obtained by each component on its own. Composites have been widely used in the industry due to its light weight and good mechanical properties. To improve these properties several layers of reinforced material (e.g., carbon fibre) are overlapped which produce an increase in the fibre consumption. In this sense Tailored Fibre Placement (TFP) embroidery can offer good opportunity to reduce the consumption of reinforced fibre while improving the mechanical properties due to the alignment of the fibres in the effort direction. This study analyzes the performance of carbon fibre reinforced composites with Polyester resin made with TFP embroidery technology against flexural strength efforts and without using plain woven fabrics to demonstrate that the use of reinforcement fabrics in composites can be optimized by a curved alignment of the fibers. Two different structures were embroidered with TFP technology, one simulating a woven fabric with straight unidirectional alignment of fibres in horizontal and vertical direction, and a second structure made with curvilinear alignment of carbon fibers. After the study of the flexural mechanical properties an improvement of 18% was obtained in maximum flexural strength.

Keywords: composites, embroidery, resin transfer moulding, tailored fibre placement, textile

1. INTRODUCTION

Composites have been used from centuries ago when first humans combined mud and straw to make adobe bricks that were used in the construction of houses. It was not until the twentieth century, when the first polymeric composite materials appeared that began to be used in automotive and aeronautical applications. Over the years, the use of these composite materials has become widespread, as they allow, with equal volume and lower density, to obtain lighter pieces with similar characteristics and in some cases with better mechanical properties than with other materials such as steel.

Glass and carbon fibers are generally the most widely used reinforcement fibres used in the composites industry due to their high strength/weight ratio [1]. In general, they include high tensile strength, good compressive strength, high tensile modulus, low density,

good thermal resistance, low thermal expansion, good electrical and thermal conductivity, and chemical resistance [2,3].

Composites reinforced with textile fibres are used in the industry due to its good properties of high strength and light weight [4]. Textile reinforcement fibers are aligned in one single direction, for this reason it is needed to combine different layers of textile fibers aligned in different directions to improve the isotropy of the composite material and its strength in the desired directions. This reinforcement textiles are limited in terms of fiber alignment due to the plain weaving technology used and the only possibility to vary the orientation and alignment of the fibers is using axial fabrics which allow to place the fiber in different angles, but all of them unidirectional in straight line, without any curve [5,6].

To obtain composites with good mechanical properties it is necessary to combine and overlap different layers of reinforcement fibers in different directions. This overlapping increases the time for processing the composite and it depends on the know-how and experience of the worker to place the fiber and reinforcement fabric all over the surface of the mould. This is a critical process as composites have better properties in the direction in which the reinforcement fabrics are aligned [7]. In this sense, Tailored Fiber Placement technology (TFP) allows the placement of the reinforcement fibers that permit to produce composites with a variable axial geometry, obtaining laminar structures with fibers aligned in multiple directions to increase the mechanical performance [8]. Tailored Fiber Placement technology is capable of manufacturing embroidered textiles with a variable axial fiber pattern by using adapted embroidery machines. This presents a novel concept for the simulation and optimization of curvilinear fiber-reinforced composites, where the novelty is based on the local optimization of both the fiber angle and the intrinsic thickness accumulation concomitantly. This is also known as Direct Fiber Path Optimization (DFPO) which is based on Tailored Fibre Placement. The key results show a clear improvement compared to the current frequently used approach where principal stress trajectories are applied for a variable axial reinforcement pattern [9]. This article confirms that in the case of structural parts that do not suffer tension stresses with conventional main trajectories (eg. tensile stress at 90°), it is necessary to arrange the reinforcing fibers in curvilinear trajectories (variable axial) in order to improve their mechanical properties.

2. OBJECTIVES

TFP embroidery technology can place the reinforcement fibres in the location where material is going to suffer more efforts and can adapt to the shape of the final object. In contrast, in the traditional composites manufacturing, the excess of fibre must be manually cut to adapt it to the shape of the desired object. This traditional manufacturing process is not very efficient in terms of fibre consumption and amount on manual tasks as it cannot be automated.

This study has the objective to evaluate the performance against flexural strength efforts of carbon fiber reinforced composites using TFP technology and without using plain woven fabrics and to demonstrate that the consumption of reinforcement fabrics (carbon, glass fibers, etc.) can be optimized by a curved alignment of fibers. Two textile structures were embroidered with TFP technology. First structure named as S-TFP (Straight TFP), simulating a woven fabric combining carbon fibers with straight unidirectional alignment in horizontal and vertical direction. The second structure named as C-TFP (Curvilinear TFP), was made with curvilinear alignment of carbon fibers, replacing the straight unidirectional fibers in horizontal direction (weft direction) by curvilinear fibers (figure 1).

3. MATERIALS AND METHODS

3.1 Materials

The carbon fiber used to develop the composites was 880TEX continuous 12K multifilament, embroidered on a 0.25 mm thick 30 g/m² polypropylene (PP) non-woven substrate. The resulting S-TFP embroidered textile had a weight of 646.79 g/m² and the C-TFP 524.15 g/m².

As matrix of the composite, a polyester (PES) resin DCPD (DiCicloPentadiene Resin) was used, to avoid contact with VOC (volatile organic compounds).

Vacuum-assisted RTM (Resin Transfer Moulding) equipment and the embroidery machine of the manufacturer ZSK were used for the formation of the composite. To cut the samples according to UNE-EN ISO 527-1:2019 a CNC machine (Control Computerized Numeric).

Finally, for the flexural strength test, the universal testing machine was used. For the flexural tests, the samples had a section of 10 x 1.2 mm.

3.2 Composites manufacturing process

First step consisted of embroider the carbon fibre on the PP substrate according to the designs defined S-TFP and C-TFP (figure 1). Once the fibre is embroiderd, it is necessary to cut the excess of PP substrate to introduce the embroidered textile in the mould to proceed with the injection of the PES resin (figure 2).

Figure 1. Designs S-TFP (left side) and C-TFP (right side); weft direction in red colour and warp direction in blue colour

Then, when the resin is injected, obtaining the final composite with the shape of the mould, in this case of study a square shape. Later, it is necessary to cut the samples according to the standard UNE-EN ISO 178:2020 for flexural effort with the 200 W Mini CNC 3040 machine (figure 3).

Figure 2. Non-woven PP substrate with embroidered carbon fibre in the RTM machine

Figure 3. Samples cutting process with a mini CNC machine

3.3 Testing process

For the characterization of flexural effort, it was used the Universal Testing Machine (IBERTEST ELIB-50-W) to evaluate the samples. Due to the characteristics of the materials and the size of the samples, the 50 kN cell was selected and a distance between supports of 60 mm was set (figure 4).

3. RESULTS AND DISCUSSIONS

The obtained results where very promising as important improvements are observed in C-TFP even using less amount of reinforcement carbon fibre. In this case, C-TFP weights 122.64 g/m^2 less than S-TFP which is a reduction of a 19% of fibre consumption.

In table 1, it is observed that curvilinear designs like C-TFP improve flexural properties, increasing the maximum flexural strength till 105 MPa against the 89 MPa obtained by the S-TFP, which represents an improvement of 18%. In terms of elasticity, the Young Module also increases when using curvilinear fibres. In this case of study, curvilinear samples (C-TFP) obtained a Young Module of 3.234 MPa in contrast with the 2.352MPa obtained by the S-TFP that does not use curvilinear fibres. This means that the C-TFP is more elastic and more resistant than the S-TFP as the Young Module and the

Flexural maximum Strength are higher. This improvement represents an increase of 37% in the Young Module for the C-TFP.

Figure 4. Universal Testing Machine used for flexural tests

Table 1. Flexural test results

Sample	S-TFP		C-TFP	
	Young Module (MPa)	Max. Strength (MPa)	Young Module (MPa)	Max. Strength (MPa)
1	2.488	93	3.405	108
2	2.333	85	3.420	105
3	2.234	89	2.876	102
Average	2.352 + 128	89 + 4	3.234 + 310	105 + 3

It is observed in the results showed in table 1 that samples with curvilinear alignment of fibres (C-TFP) improves the flexural strength properties.

One of the reasons which can explain this improvement of flexural properties with less amount of reinforcement fibre is the phenomenom of efforts decomposition in normal forces (figure 5).

When a generic effort called “F” is applied in warp direction a response is generated in the same direction but in the oposite sense. In the case of the S-TFP the response obtained in the weft direction is 0 as do not offers opposition or resistance.

$$F = F2 + F3 = F2 + 0 = F2 \quad (1)$$

However, in the case of C-TFP the effort applied in the curved fibres is decompose into normal forces improving the behaviour of the composite against an effort “F”.

$$F = F2 + F1y = F2 + F1 \cdot \sin(\alpha) \quad (2)$$

This is the reason why composites reinforced with curved fibre alignment offers a better response againts flexural efforts even using less percentage of reinforcement fibre.

Figure 5. Schema of effort decomposition; on the left S-TFP and on the right image C-TFP

5. CONCLUSIONS

Composites with straight axial fibre placement like S-TFP have a good behaviour and good mechanical properties when the stress goes in the same direction than the fibre. In contrast, they obtain bad results when the stress is applied in a different direction (e.g., perpendicular) to the fibre. On the other hand, composites with aligned curvilinear fibres obtain better results due to the superposition of forces ($F_2 + F_{1y}$) and the phenomenon of loads decomposition into normal components (vertical and horizontal) as described in figure 5 and equation 2 along the fibres and interface of the resin matrix. This decomposition of efforts explains why the maximum flexural strength is higher in C-TFP than in S-TFP, since the added forces in C-TFP are greater than the force supported by S-TFP.

In this case of study, it is obtained an improvement of 18% of flexural maximum strength, using the same amount of fibre in both composites or even less fibre like in C-TFP and without increasing the costs. This increase of 18% can be considered very interesting in some industrial sectors and for high technique and added value applications like in automotive or aerospace industry. In this sense, C-TFP is less rigid than sample S-TFP and has a more elastic behaviour.

Also, for some specific applications not only strength but also elasticity is a very important factor to be considered due to its implications in aerodynamics. In this sense, curved oriented fibres has lot of potential as can improve both, elasticity and strength.

Nowadays this new and promising research line is researching new textile structures made with Tailored Fibre Placement technology with the objective to obtain composites with better mechanical properties.

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