Development of a Laboratorial Robotized Filament Winding Equipment

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ABSTRACT: Filament winding is the mostly suitable technology to produce at large volume scale structural composite parts presenting revolution form, such as pressure and non-pressure vessels, tanks and pipes, aircraft fuselage, helicopter blades, etc.. Such process allows optimising the deposition and orientation of continuous reinforced fibres in order to manufacture the best performance and customised composite part for each specific application. Another advantage of this technological processing method is the possibility it gives of using almost all continuous reinforcing fibres (carbon, glass, aramid) and plastic matrices (both thermosetting and/or thermoplastic). As the investment for acquiring a filament winding equipment was too much high, the Pole for Innovation in Polymer Engineering (PIEP) decided to use its proper know-how to self-develop an own robotised filament winding equipment for laboratorial use. The aim of such equipment is to support R&D projects with industrial companies concerning the production of filament wound scaled prototype parts for testing, optimising and improving fibre deposition trajectories, study the complex shape manufacturing, testing the application of new fibres and matrices, etc. This paper will present the developed and built robotised filament winding equipment and will discuss its major possibilities, trajectories and software data acquisition capabilities and the results obtained on composite parts manufactured by it.

1 INTRODUCTION

1.1 *Filament winding*

Filament winding is a production method consisting of continuous fibers. In case of a wet system, the fibers are impregnated trough a resin bath. Tension is applied before, during and after impregnation; during impregnation to let the resin into every part of the fiber, before and after to keep the fibers straight and maintain constant the fiber band pressure when it is wrapped around the tool. This pressure will have a big influence on the content of fiber in the part, COHEN (1997). After passing through the resin bath, the fibers go to a payout eye, which allows deposit accurately the band of fibers with the desired oriented angle on the rotation mandrel. The payout eye is usually mounted on a carriage to follow the defined required trajectory. When pre-impregnated or thermoplastic matrix materials are used, the impregnation system is usually abolished from the filament winding equipment. In such cases, a heating device must be mounted to get these materials tacky. Filament winding are usually used to manufacture structures of revolution presenting high mechanical performance, such as: pressure vessels, pipes, oxygen & other gas cylinders, rocket motor casings, helicopter blades and small and large storage tanks for above and below ground applications, fuel tanks, spherical vessels, etc.

The filament path and therefore the fiber orientation have a big influence on the final part strength and stiffness. For different loading situations, different paths have to be chosen. The winding angle is the main parameter for the winding path. Generally there are three winding types regarding the angles as can be seen in Figure 1: circumferential, helical and polar.

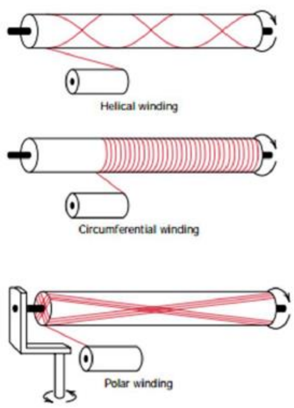

Figure 1. Three different types of winding.

In circumferential winding, both carriage and payout eye move in translation at ratio of one fiber bandwidth per each mandrel rotation, which results in a deposition at angle of continuous fibers close to 90° relatively to the equipment rotational axis. Helical winding allows obtaining the so-called angle-ply laminates, characterized for presenting ±α sequences of ply angles. As the circumferential stress usually doubles the axial one in pressure vessels and pipes the optimal laminate for them use layers oriented at angles of ±54°. Finally, in polar winding the fiber band is made to pass close to the mandrel extremities in order to allow producing simultaneously the cylindrical and dome parts of vessels by using much lower angles, close to 0°, relatively to the rotational axis.

While circumferential and helical windings may be achieved through the so-called conventional helical filament winding machines, polar ones require the use of much more sophisticated programmable equipment able to avoid slippage resulting from the use of winding angles approaching 0°. Sometimes winding pins may be required to cope with this problem, VASILIEV (2009).

Today, the demanding for automatic machines able to produce composite parts in large series is increasing. Automatic filament winding and tape placement not only offer such possibility but also the chance to position and optimize the fibers orientation accordingly to the mechanical design, requirements and performance of final products, POTTISH (2005).

Therefore, PIEP is very interested in developing know-how on these production methods to supply its partners and clients with better services, by taking into account that currently available filament winding equipment is rather complex and require large investment.

Considering the limited degrees of freedom on fiber deposition given by current available machines a six-axis robot was chosen to be used on our own developed filament winding equipment. The use of a robot had made the process becoming more flexible, less expensive and able to be used in multiple projects. A main goal of the project will be to use such developed equipment later to process products by tape placement by using thermoplastic and thermosetting pre-impregnated materials.

2 SYSTEMS AND TOOLS FOR THE EQUIPMENT DEVELOPED

2.1 *General characteristics and capabilities of the robot*

A Motoman® HP20 robot and a NX100 controller, both produced by Yaskawa, were used in the developed filament winding equipment. This kind of robot is most often used in pick-up and place on operations. It has six-axis, which makes possible movement with six degrees of freedom adopting two different coordinate systems: the Cartesian and/or polar one, using an axis origin located on the robot base or any other one defined by the user.

An industrial motor was used to produce the rotational movement of the longitudinal tubular mandrel.

2.2 *Impregnation unity*

Wet filament winding tests were conducted in the present work by using a thermosetting resin in the developed equipment. The process requires impregnating well the fibers with resin to obtain a proper laminate with the desired properties. The two following described impregnation systems were developed and tested: one consisting in a syphon impregnation unit and the other in an open impregnation process having a payout eye and a resin bath.

2.2.1 *Syphon impregnation*

The used syphon impregnation system has been developed at the Institut für Verbundwerkstoffe (IVW), from Kaiserslautern/Germany. Such impregnation technique consists on a closed system based on a curved tube.

The continuous fibers and resin are made to enter from one of extremities of a plastic curved tube and, then, transport along it in order to achieve the total fiber impregnation due to the generated pressure. A second purpose of the curve is providing the desired fiber tension, which allows flatten the fiber, better impregnate it as well as obtaining a higher winding tension. This system is shown in Figure 2.

Figure 2. Syphon impregnation unity applied in the robot.

Initial tests were done using two different curves in the syphon system: one having a larger angle than the other, which results in a lower fiber tension. During this initial tests made by using one fiber and an Epikote epoxy resin, best fiber impregnation results were obtained with the small angle curve. Hence, this curve is used for further tests and the system was also expanded to use four continuous fiber roving's.

2.2.2 *Open impregnation*

Open systems usually use two major techniques to impregnate fibers: a wet cylindrical rolling drum or the dip in resin bath. In both processes flatten fibers are impregnated through an open resin bath. In the first one, fibers are made to pass pressed on the upper side a rolling cylindrical drum partly immerse in a resin bath. The resin stuck to the upper side of the rolling drum is transported to the fiber and impregnate it.

In dip-resin bath process, fibers are forced to plunge guided into a resin bath kept in a suitable container. This technique that offers higher speed and lower fiber content and quality of impregnation is usually used with more easily impregnable reinforcements, like glass fibers.

The wet drum technique, which is slower but gives better resin control, is typically used with carbon fibers systems that require more wet out and higher fiber contents, POTTISH (2005).

In the present work, a dip-resin bath based process was developed and designed to be applied in glass fibers impregnation. Figures 3 and 4 show an overview of the payout eye and resin bath container developed for such purpose, respectively.

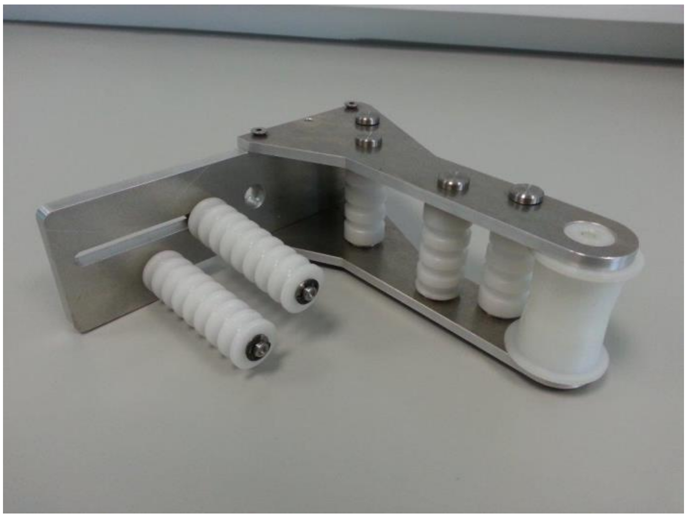

Figure 3. Payout eye used in the dip-resin bath process.

Figure 4. Resin bath container.

2.2.3 *Comparing the syphon and open impregnation processes*

Tests demonstrated that the syphon process offers the following benefits:

- compact and modular construction, possibility to mount on carriage;
- no limitations in respect to pot-life because resin is continuously fed;
- clean impregnation near the winder, minimizing resin leakage and its exposure to air and moisture;
- easy cleaning of impregnation device;
- easy and cheap to build.

On the other side, the benefits of the open impregnation are :

- different components enable separate optimizing;
- easy and quick to prepare;
- easy to reapply a broken fiber.

3 THE PRODUCTION PROCESS

The different parts of the equipment were combined in order to build the final winding production process. Then, several tests were performed to verify components, and adjust and approve their integration. In total, about ten production tests were made using a 76 mm diameter tubular mandrel and a plate. Several adjustments were made concerning, for example: winding speeds and angles, fiber guiding and increase the number fibers used from one to four.

3.1 *Used tools and materials*

The following tools and equipment are used:
- robot: Yaskawa Motoman HP20;
- controller: Yaskawa Motoman NX100;
- syphon impregnation;
- mandrel rotational motor: asynchronous three-phase motors;
- fiber guiding, general material: transparent tubes having 4 mm inside diameter, a peristaltic pump Autoclude AU V025 01 and Y-connectors Watson Marlow pumps Kynar;
- mandrel: round tube with a diameter of 76 mm.

Raw-materials:
- glass fiber, TufRov 4599, 1200 TEX;
- resin: 23% Epoxy Hardener EPH04908 and 77% epoxy resin Epikote 862.

3.2 *The program*

To perform the tests it was necessary to program the interface to control the robot. As the robot present linear movement between two points to make possible to realize the desired winding angle the payout eye needs to rotate.

Therefore, four more points are needed. In total, six points were created as Figure 5 shows.

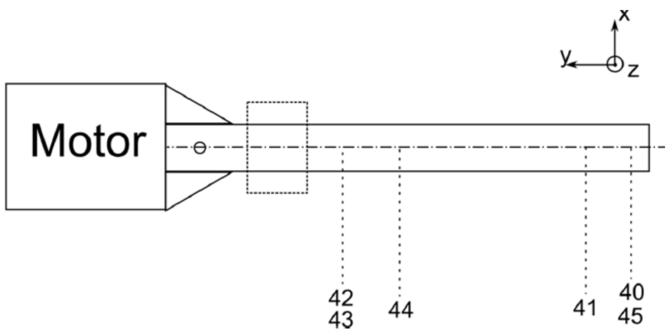

Figure 5. Sketch of the mandrel and position of the points.

The work starts at point 40 with an angle of 0°. Then it moves to point 41, rotating to the desired winding angle. As Table 1 shows for test 4, the winding angle is set to 54°. At the beginning, as the angle needs to be rotated 90°, the input value was taken as 36°. Then, the angle will stay the same till point 42 and, then, will rotate until 0° at point 43. A time pause was introduced at this point to let the fiber catch up with the payout eye to ensure a good turning point with low fiber slipping over the mandrel, which usually occurs during too quick turnings. Thus, after a pause of two seconds, the payout eye starts rotating to -36° at point 44 keeping moving until point 45, where it waits 2 s another time, rotates to 0° and with a jump command to the starting label, completing the loop cycle. The rotational speed (VR) was set in 30°/s.

Table 1. Overview of test 4, coordinates in respect to base system

Robot point	X	Y	Z	R_Z	V | VR
number	mm	mm	mm	Angle	mm/s | °/s
40	1200	-100	670	0	VR=30
41	1200	-30	670	36	V=159.1
42	1200	230	670	36	V=159.1
43	1200	230	670	0	VR=30
44	1200	160	670	-36	V=159.1
45	1200	-160	670	-36	V=159.1

Mandrel speed: 20 RPM; Angle: 54º; 2 and 3s turn time; Pump speed: 20 RPM.

3.3 *Production test*

After setting the syphon impregnation unit by comparing the amount of the resin coming from the peristaltic pump with rotational pump speed (RPM), the first trial of tests was made. The two initial tests were done to verify if impregnation was achieved in good conditions by rotating a carton tube by hand. This was a time and labor consuming process.

Production is then improved by using the robot instead of manual winding. A similar program to the one above described in Table 1 was used. Several winding angles from 30° to 90º were tested . After that, the syphon impregnation was expanded to four fibers as may be seen in Figure 6.

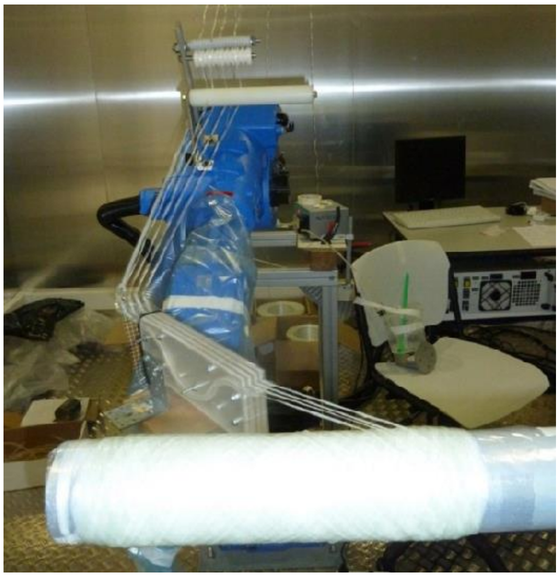

Figure 6. The filament winding with four roving.

Since problems were found to keep the fibers separated a new guiding system was developed. Such system allowed to create a new fiber path at the ceiling and kept fibers separate until the mandrel in order to produce successfully and in good conditions filament wound pipes. Figure 7 shows one of these typical produced pipes.

Figure 7. A successfully filament wound pipe produced by using the new developed equipment.

4 FINAL SETUP

After validating the concept a most robust equipment was developed by using a kit constituted by the three following systems: a drive unit, a mobile unit and the robot (Yaskawa Motoman IA20), as Figure 8 shows.

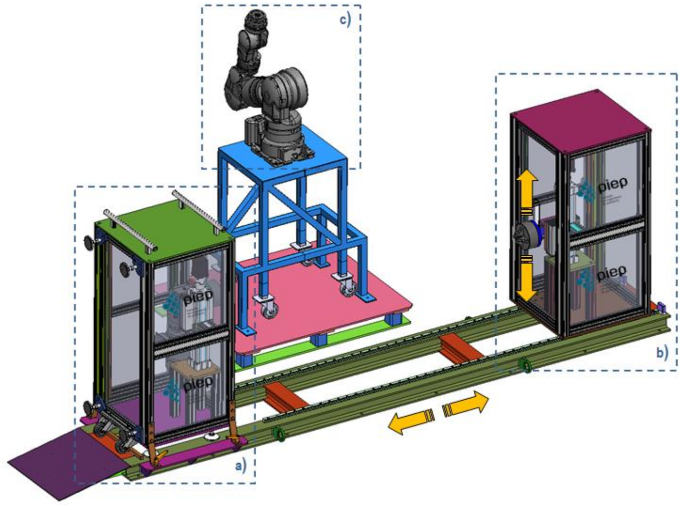

Figure 8. Final filament winding kit.

The drive unit, a), constitutes the servo system and is responsible for the rotational movement of the two components responsible for height adjustment and driving. Such unit is synchronized with the mobile unit and the concentricity between bushings allows controlling the mandrel ascending and descending movements (including when processing). The drive unit has a variable speed from 0 rpm to 160 rpm and maximum torque of 83 N.m.

The mobile bushing unit b) monitors the movement of rotation in sympathy with the above mention driving bushing unit.

Finally, the selected robot c), consists in a anthropomorphic arm Motoman IA20 with seven degrees of freedom and accuracy of +/-0,1mm.

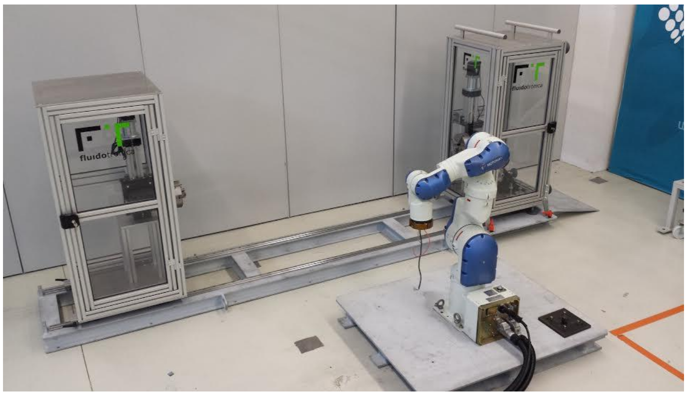

Figure 9. Filament winding kit assembly.

5 CONCLUSIONS

In this work, a lab scale customized filament winding equipment was developed by using a robotic arm and its controller.

Two kinds of impregnation unities were developed and tested: one consisting in a syphon system and another based on an open impregnation process.

All developed filament winding concept was validate by using real tests and the built equipment used to produce filament wound pipes in good conditions.

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