Filament winding technique, experiment and simulation analysis on tubular structure

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Abstract. Filament winding process has emerged as one of the potential composite fabrication processes with lower costs. Filament wound products involve classic axisymmetric parts (pipes, rings, driveshafts, high-pressure vessels and storage tanks), non-axisymmetric parts (prismatic nonround sections and pipe fittings). Based on the 3-axis filament winding machine has been designed with the inexpensive control system, it is completely necessary to make a relative comparison between experiment and simulation on tubular structure. In this technical paper, the aim of this paper is to perform a dry winding experiment using the 3-axis filament winding machine and simulate winding process on the tubular structure using CADWIND software with $30°,45°,60°$ winding angle. The main result indicates that the 3-axis filament winding machine can produce tubular structure with high winding pattern performance with different winding angle. This developed 3-axis winding machine still has weakness compared to CAWIND software simulation results with high axes winding machine about winding pattern, turnaround impact, process error, thickness, friction impact etc. In conclusion, the 3-axis filament winding machine improvements and recommendations come up with its comparison results, which can intuitively understand its limitations and characteristics.

Keywords: Filament winding technique, dry winding, CADWIND software simulation, tubular structure

1. Introduction

The composite material has been gradually recognized by the many advanced material industries and researchers as a potential engineering material, which can replace the conventional and general materials in producing light-weight and low-cost products. Filament winding is a mature manufacturing process in the composite material, which can produce a wide range of moderate and high mechanical performance parts. For more than 30 years the primary aim of filament winding process and development, this technique has been evolved into automated advanced composite materials with different structures. The industries and companies are looking for the light-weight, high mechanical performances and cost savings. There are many types and sophisticated development in modern filament winding for the initial process, which collects different type fibres are continuously wound on a rotation supporting form or mandrel with the different winding angle. The first filament winding machine was developed in 1950 in accordance with the revolutions of the filament winding application [1]. Filament wound applications are applied to make tube-shaped or pipe-shaped production such as high-pressure storage tanks, rocket motor cases, and launch tubes. For commercial applications, filament wound products can be used for commercial equipment such as golf club shafts and fishing rods [2].

Filament winding machine also has been developed based on its high mechanical performance products. Filament winding machine structure has been evolved from 2 axes classical lathe-type winder towards high axes winders with an accelerated degree of freedom, which can promote filament

winding machine processing capability. With advances in technology, standard industrial robots have been put it into use in the composite fabrication process. Figure 1 shows COMEC company product filament winding robot. It overcomes the filament winding process weakness in a proper way, which lightens the filament winding development orientation.

For the sake of filament winding process development, many researchers have focused on improving filament winding machine axes, mechanical performances, and material properties experiments on filament wound composite products. It can be divided into two parts, which are filament winding machine development and filament wound composite product experiments. F.H.Abdalla et.al have demonstrated that a 2-axis filament winding machine was designed and fabricated as pipes and round shape specimens [3]. M.R.M.Rejab et.al have proposed four axes filament winding machine modification and machine structure [4]. Saad Mutasher et.al performed experimental investigations on small-scale automated filament winding machine controlled by a single PIC 18F452 microcontroller. Winding test of the prototype shows that it is capable of producing winding angles in the range of 40 to 80 degree[5]. The filament winding process has faced limiting fabrication obstacles, which can try to design complex geometries of the composite structure. E.Vargas Rojas et.al have discussed the challenges and validates a generic mathematical model that contributes either to wind complex shapes or solve common filament winding disadvantages on basis of an integrated strategy [6]. However, there are no related studies examined using 3-axis filament winding machine experiment products compared with CADWIND software simulation results, which can have a good understanding and comparison results to improve the tested machine process capability.

Another winding research branch is to perform and analyze the filament wound composite products, which can get high mechanical performances. A.Zuraida et.al have investigated the experimental and finite element analysis for hybrid and non-hybrid glass and carbon/epoxy composite tubes subjected to quasi-static lateral indentation loading. A useful comparison was done for the tested composite tubes between the finite element and the experimental results, which shows that carbon/epoxy tubes resist higher load with less deformation the glass and hybrid glass-carbon tubes [7]. Xiaolong Jia et.al have noted that the cylinder with end reinforcing layer had higher compressive properties and sequentially showed brittle fracturing model, local buckling model and transverse shearing mode with winding angle increasing [8]. Previous research has shown that composite products can have quite potential properties to replace common material in the next time.
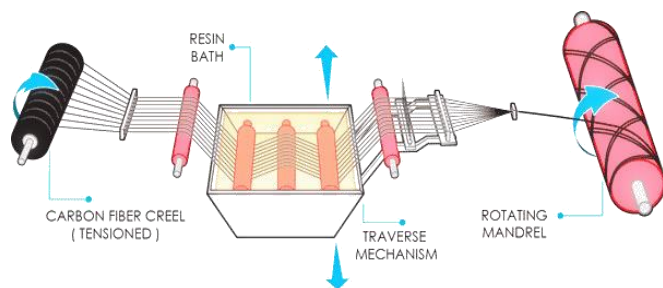

Figure 1: Filament winding robot prototype [9]   Figure 2: Filament winding process schematic [10]

1.1 Filament winding

Filament winding is a process in which the resin and fibres through the resin bath, which is wound on a different shape of the mandrel with controllable speed. In filament winding method, fibre strands or tows are wound and steadily passed through the resin bath. In the resin bath, fibre strands are impregnated with the polyesters or epoxy. Then related resin impregnated strands are wound on a rotating mandrel in a controlled system with specific fibre orientation, which can implement different winding angle based on customers' requirements.

The schematic of filament winding process is shown in Figure 2. Fibres are collected and put in the order through a comb, and then fibre strands are wetted with the resin in resin bath. Furthermore,

fibre with the resin passes through another comb and a pay-out eye device. During the process, traverse mechanism can move forward and backward in the delivery system. In addition, fibres with impregnated resin are wound around a rotating mandrel at various winding angles to satisfy mechanical requirements, such as strength, elasticity, ductility, stiffness and fatigue strength. The tubular structure is then cured at ambient temperature or special temperature and the mandrel is removed. To remove the mandrel from the composite products, hydraulic rams may be used on different filament winding machine. Hollow pipe and other shape parts are fabricated via filament winding technique. Fibre tension force is critical specification in filament winding because compaction is achieved by the fibre tension, which is a necessary parameter should be under control. The fibre tension will affect the properties of the composite products. There are many tension device types such as magnetic or friction brakes, electronic rewind, rotating scissor bars and high-performance solenoids. Filament winding has another main advantage is that a high fibre volume fraction can be achieved in the composite material with filament winding process technique.

1.2 Filament winding pattern generation

Filament winding technique has three winding patterns, which are the hoop, helical and polar winding. Most filament wound products are produced by means of the helical winding pattern. In helical winding method, the fibre tow is wound on the mandrel with a moderate angle to the longitudinal axis. The winding process focuses on a tubular structure specimen, which can summarize as follow. The main aim is to cover a cylindrical mandrel completely with a constant thickness of the fibre tow. At the start of the dry winding process, the fibre tow is deposited at the left side of the mandrel and wound with a constant winding angle to the right side of the mandrel. The first movement path is named a passage, which can be illustrated in Figure 3 (a).

At the end of this passage, the transverse motion of the pay-out eye unit is stopped and prepared to reverse with the fibre tow to change the direction. During the reverse motion, the mandrel can still keep the rotation, which can wind between the end of the first passage and the beginning of the second passage. The fibre tow can be wound toward the left side from the right side of the mandrel. The two passages are called a circuit. It can be demonstrated in Figure 3 (b). At the end of each circuit, it has a constant value to add between next successive circuits, which are plotted in Figure 3 (c). The final winding pattern depends on increasing value, which can directly control the rotation angle between each passage. The rotation angle at each side of the mandrel is a means of controlling filament winding structure based on the filament winding angle. Filament winding pattern can be presented by a regular diamond-shaped cell, which is shown in Figure 3 (d). In the diamond-shaped cell, it is simple to come up with laminated $+\varphi/-\varphi$ fibre orientation.

a. First passage   b. First circuit (Second passage)

c. Third passage   d. Double fibre $+\varphi/-\varphi$ orientation
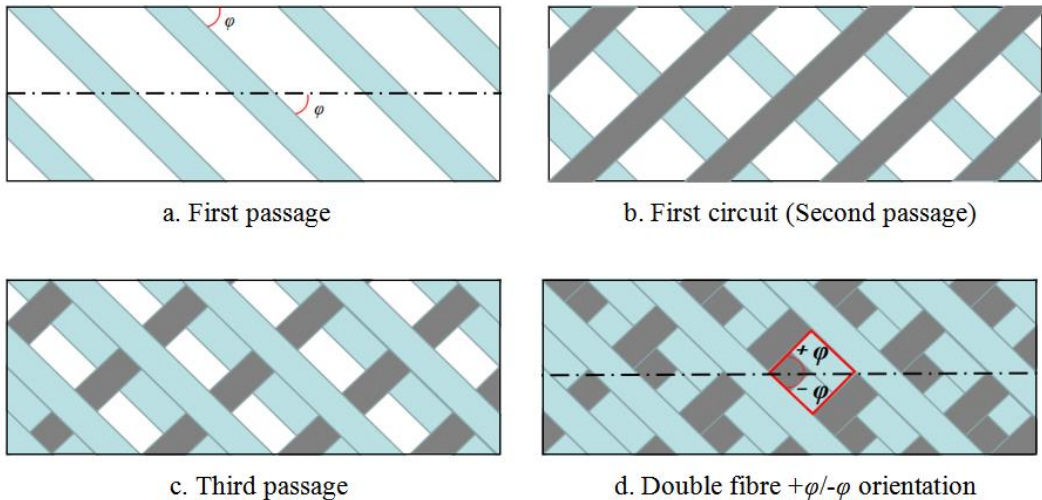
Figure 3: Filament winding process generation: (a) first passage, (b) first circuit, (c) third passage, (d) double fibre $+\varphi/-\varphi$ fibre orientation

1.3 Filament winding angle and turnaround zone

The fibre is wound and completed one full cycle through entire mandrel length, which one circuit is formed. One layer is the number of patterns required to cover the entire mandrel surface with fibre. The mathematical calculation should formulate and demonstrate winding angle, which can refer to the winding pattern, winding circuit[5]. It has two methods to calculate the winding angle, which is displacement calculation and velocity calculation. Because of 3-axis filament winding machine control system, displacement calculation method has been chosen to implement expected winding angle. The length of the filament wound cylinder is 210mm, $X_1=X_2=X_3=210$mm. Based on the triangle formula, 60° winding angle, 45° winding angle, and 30° winding angle calculation schematics are shown in Figure 4.

$$Y_1 = \tan 30^0 \times X_1 = 121.245 mm \tag{1-1}$$

$$Y_2 = \tan 45^0 \times X_2 = 210 mm \tag{1-2}$$

$$Y_3 = \tan 60^0 \times X_3 = 363.730 mm \tag{1-3}$$

Mandrel shape has chosen a tube, almost winding parameters are fixed by the fibre tow and winding pattern. Their parameters are the tubes radius R=19mm, the winding angle and the bandwidth of the tow b=2mm. With the following equation, it can have access the number of circuits P necessary to obtain complete mandrel coverage with a double layer [11]:
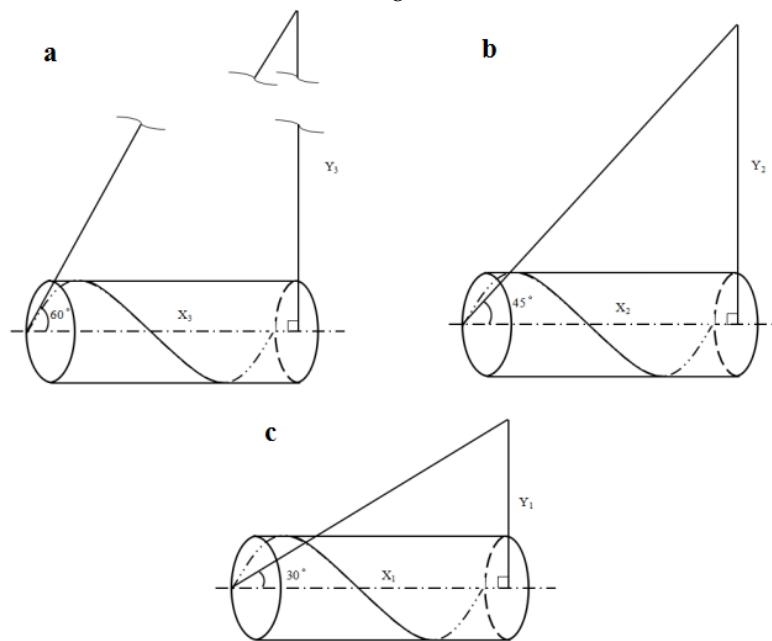
$$P = \frac{2\pi R \cos \varphi}{b} \tag{1-4}$$

Figure 4: Filament winding angle displacement calculation schematic: (a) 60°winding angle, (b) 45° winding angle, (c) 30°winding angle

In the above basic equation, it is obvious that the number of a circuit should be an integer. Therefore, the bandwidth value can be adjusted slightly. As an example, the winding angle is calculated using φ=45°. Other filament winding angles can be calculated with the same method, which can only change the winding angle value. Figure 5 is presented filament winding parameter calculation diagram, which can easily handle calculation formulation.
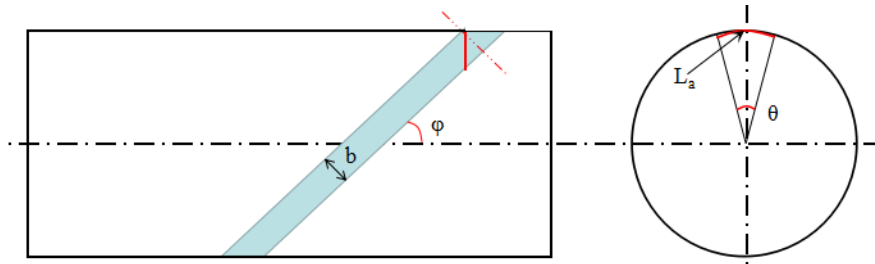
Figure 5: Filament winding parameter calculation schematic

Mandrel circumference C_m:

$$C_m = \pi \times d = 3.14 \times 38 = 119.320 mm \tag{1-5}$$

Curve length L_a:

$$L_a = \frac{towwidth}{\cos \varphi} = \frac{2}{\cos 45^0} = 2.828 mm \tag{1-6}$$

Rotation angle θ:

$$\theta = \frac{360^0 \times L_a}{C_m} = \frac{360^0 \times 2.828}{119.320} = 8^\circ 31' \tag{1-7}$$

One circuit the rotation angle can increase:

$$2\theta = 16^\circ 62' \tag{1-8}$$

Circuit number N_c:

$$N_c = \frac{360^\circ}{2\theta} = \frac{360^\circ}{16^\circ} = 22.5 \approx 23 \tag{1-9}$$

The turnaround area in the filament winding process is the area where the fibre orientation starts to change the winding angle in order to come back to wind another side[12]. The winding angle can gradually increase until hoop winding and then reduce to expected winding angle. Most wasted filament wound products happen in the turnaround area, which is an inevitable process. It can lower the wasted material to reduce the turnaround zone area and process time. This can be achieved by adding the hoop winding on both sides, which can decrease the fibre slippage condition. The turnaround zone method schematic is shown in Figure 6.
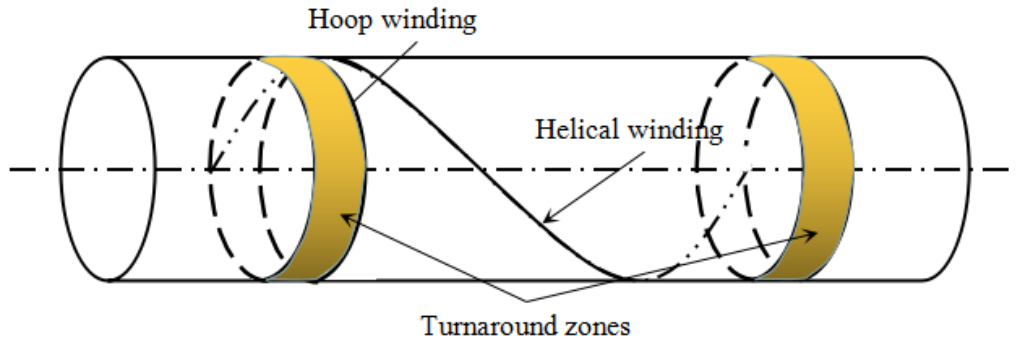

Figure 6: Turnaround zones diagram

2. Methodology

Research methodology in this technical paper can be separated into three steps, which will describe details as follows:
Step 1: Calculation and write filament winding codes
• Based on the 3-axis filament winding machine parameter settings, filament winding codes should be properly written with different winding angles.
• Before taking the next step, the operator needs to check and run without wool yarn or carbon fibre. It is quite necessary to run the machine that can decrease mistakes.
Step 2: Perform filament winding experiments with 30°, 45° and 60° winding angle

• Prepare the experiment components such as the 3-filament winding machine, a wool yarn spool, power plug, USB wire, the PC, protractor, Universal G-code Sender software (UGS) and tested filament winding codes

• Connect USB wire and power plug, then fix the wool yarn one side on the mandrel with packaging tape. Next upload the different winding angle UGS codes in UGS software *File mode* sub-interface

• Finish filament winding process completely and measure the winding angle using the protractor

• Check the mandrel coverage rate, repeated pattern, product shape.

Step 3: Filament winding simulation using CADWIND software

• Have a brief introduction to CADWIND software, and learn the method to get proper simulation results

• Based on the previous filament winding experiment parameters and condition, the operator sets suitable parameter simulation values and click *"Start winding"* button. Eventually, the build-up of the different winding angle tubular products can be shown with the isometric view and front view.

Step 4: Comparison 3-axis filament winding machine tubular structure results with CADWIND simulation results

• Compare the 3-axis filament winding machine manufacturing capacity with CADWIND simulation process

• Compare experiment results with CADWIND simulation results about mandrel coverage rate, repeated characteristic pattern, winding structure and turnaround area pattern.

• Make a conclusion about 3-axis filament winding machine working capacity, which can demonstrate its advantages and disadvantages, products quality. The most important point is that it can give many pertinent suggestions on the 3-axis filament winding machine improvement, CADWIND software evaluation and related UGS codes optimization.

$45°$ winding codes have been explained as follows, which set an example in this paper to write the winding codes. Based on the 3-axis filament winding machine system, Y-axis is the mandrel rotation. The 1 revolution means that the mandrel can rotate 1 full rotation, which moves mandrel circumference length. The $45°$ winding codes can be written based on the above calculation. The one circuit of the $45°$ winding code is shown in Figure 6. Based on the equation (1-9) calculation result, the total winding code can repeat 23 times to build the winding code.

$$\frac{1}{C_m} = \frac{N_2}{Y_2} \tag{1-10}$$

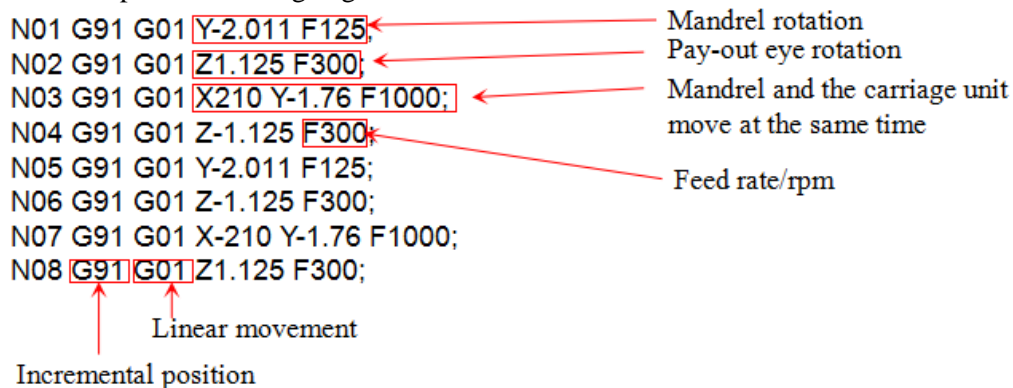Y-axis rotation step of 45 winding angle N_2:　$N_2 = 1.76$ $\tag{1-11}$

Figure 6: $45°$ winding code interpretation

3. Experiment using the 3-axis filament winding machine

The 3-axis filament winding machine has been designed with the inexpensive control system, which is still in process testing state. The main objective is to use the portable, high accurate 3-axis filament winding with the inexpensive control system, which can fabricate the filament wound

composite tubes with different winding angles. The 3-axis filament winding machine is used in experiment process, which can perform dry winding. The 3-axis filament winding machine is developed by the author, which is strongly supported by Human Engineering Group Lab, Faculty of Mechanical Engineering, Universiti Malaysia Pahang.

3.1 Experiment setup

The 3 axes experimental filament winding machine should be put on a flat table or workbench. Figure 8 presents the tested machine on the operating platform. This machine is used to apply carbon fibre (Pyrofil TR30S 3K), but it will increase the experiment costs and waste too much carbon fibre for further tests. This kind of carbon fibre type width is 2mm and the approximate thickness is 0.13mm of the 3K tow. It can decrease the machine movement accuracy rating to a certain extent. However, a pink wool yarn is chosen as the dry winding testing filament, which has approximate 1mm width. Figure 9 displays the wool yarn ball details, which is fully convenient to perform dry winding process especially in fibre path and repeated winding pattern.
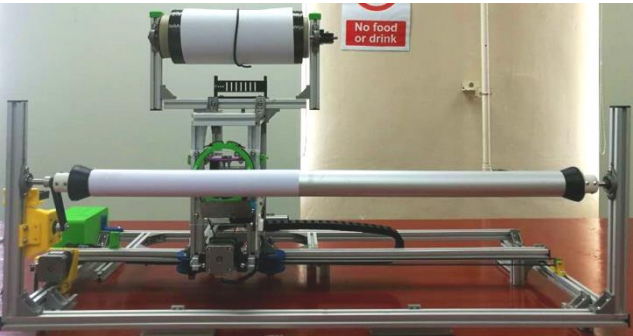
Figure 8: 3-axis filament winding machine

Figure 9: 100% wool yarn[16]

The experiment sets upon a proper position, which can simply perform filament winding process. The setting structure can be shown in Figure 10. The wool yarn string should be pasted on the mandrel, which can use packaging tape. Figure 11 illustrates preparation work on the mandrel. An A4 paper covers on the aluminium mandrel, which can provide a constant surface friction. The wool yarn path plotted in Figure 12 clearly shows the wool yarn trajectory through the resin bath (without resin), nip roller device, comb guide, guide roller, pay-out eye and pay-out eye comb.
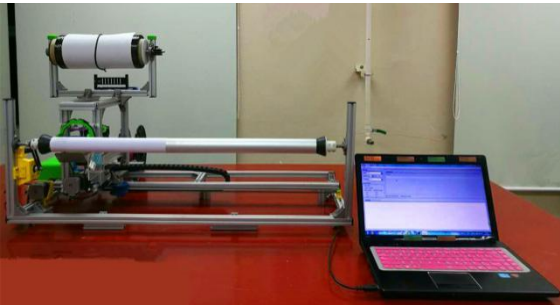

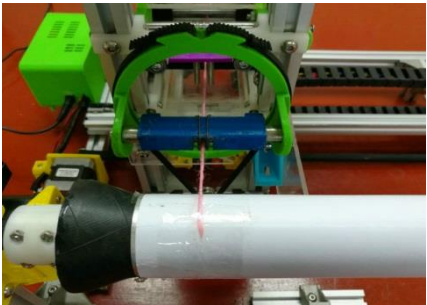Figure 10: Experiment position setup
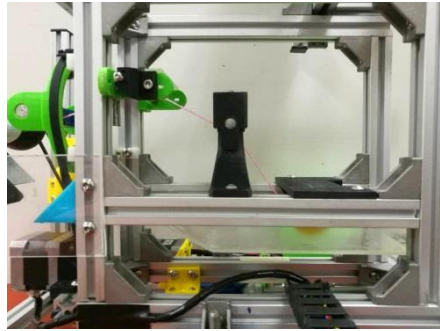

Figure 11: Paste wool yarn on the mandrel

Figure 12: The wool yarn trajectory on the carriage unit

3.2 Perform experiments with 30 °, 45 °, and 60 ° winding angle
3.2.1 Experiment with 30 ° winding angle

The 30 ° winding angle UGS codes save as text. Then upload the 30 ° winding angle codes on *File Mode* and click "Send" button, the 3-axis filament winding machine can automatically perform filament winding process with 30 ° winding angle. Figure 13 shows the upload interface when it accomplishes. Figure 14 supplies detection result using the protractor at 30 ° winding angle.30 ° winding angle experiment product is illustrated in Figure 15, which appears some voids and fibre slippage.

30 ° winding angle

Figure 13: Complete interface with 30 °
winding angle
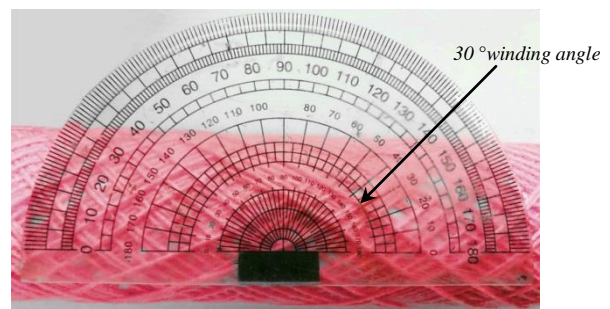
Figure 14: Measurement using the protractor with
30 ° winding angle

Figure 15: 30 ° winding angle experiment product with front view

3.2.2 Experiment with 45 ° winding angle

The 45 ° winding angle UGS codes should be saved as text. Then upload the 30 ° winding angle codes on *File Mode* and click "Send" button, the tested filament winding machine can automatically implement filament winding process with 45 ° winding angle. Figure 16 shows the upload interface when it accomplishes, which has a longer time compared to 30 ° winding angle. Figure 17 supplies measurement result using the protractor at 30 ° winding angle. 45 ° winding angle experiment product is illustrated in Figure 18, which can simply recognize diamond-shaped unit cell.

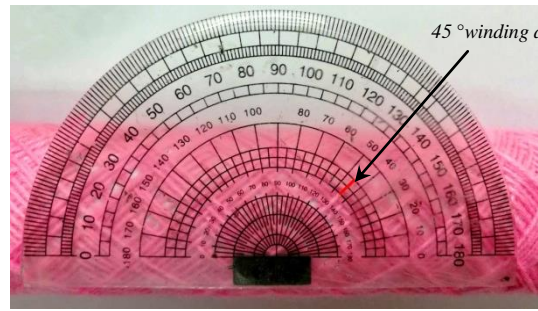Figure 16: Complete interface with 45 ° winding angle

Figure 17: Measurement using the protractor with 45 ° winding angle

Figure 18: 45 ° winding angle experiment product with front view

3.2.3 Experiment with 60 ° winding angle

The 60 ° winding angle UGS codes save as text. Next upload the 60 ° winding angle codes on *File Mode* and click "Send" button, the 3-axis filament winding machine can willingly carry out filament winding process with 60 ° winding angle. Figure 19 shows the implementation interface. Figure 20 provides measurement result using the protractor at 60 ° winding angle. 60 ° winding angle experiment product is exhibited in Figure 21, which have a good winding pattern generation with diamond-shaped cell unit.

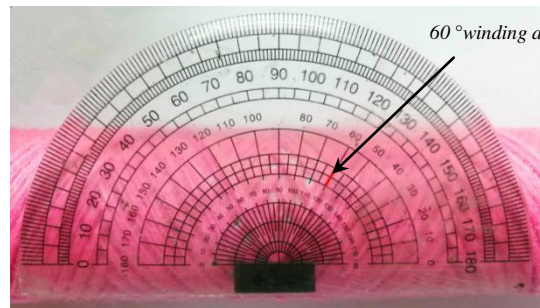Figure 19: Complete interface with 60 ° winding angle

Figure 20: Measurement using the protractor with 60 ° winding angle

Figure 21: 60 ° winding angle experiment product with front view

4. Filament winding simulation

The CNC technique and computer evolution have provided a critical leap in filament winding. It supplied the competence to control the fibre placement, mandrel rotation, and control system accuracy,

which makes the possibility of interaction between the CNC machine and the innovated simulation software. This interaction can allow the CNC machine to make more complex shapes and have a high precision for products. During the years many CAD/CAM software and environments were developed which would enable a user of a CNC-controlled filament winding machine the possibility of designing parts for different mandrel shapes and produce their own parts[13].

In the filament winding process research field, some related CAD/CAM software for the filament winding applications have been applied. Such as ComposicaD^{TM}, CadPath^{TM}, fibreGraphix^{TM}, CadFil^{TM} and EasyWinder^{TM}. This kind of software can provide degrees of control systems codes before the process and different symmetric or unsymmetric filament wound products, product material data collection and analysis output, filament winding simulation process and FEA (Finite Element Analysis) mesh output and graphical user interface. Besides above available software, Matlab^{TM} software can also simulate filament winding process via Pathwind, which is the software that aims to simulate filament winding along axis-symmetric mandrels. It can generate paths and patterns for different mandrel geometries and tow properties as well as generate CNC code for filament winding machines. This software was first developed as part of a Master thesis while working in INEGI[12].

4.1 CADWIND Software introduction

Filament winding is one of the more sophisticated methods of producing composite products, which can calculate the complex movements of up to six axes machine on CADWIND software. The development of CADWIND, which simulates on the basis of a physical model the winding process on the computer, calculates the fibre lay-up on the mandrel and automatically generates the related program codes for the six-axis filament winding machine[1]. CADWIND has progressed development from academic research projects to Material S.A company standard for different kinds of filament wound products. Over 300 research institutes, universities and companies are using CADWIND software to simulate filament winding process.

4.2 CADWIND simulation

The procedure working principle of CADWIND consists of three steps. Details are as follows[14]:
Step 1: Creating the mandrel model;
Step 2: Calculating the winding process;
Step 3: Generating the part program code;

Step 1: Creating the mandrel model
1. Choose the menu *FILE/CREATE MANDREL/CIRCULAR CROSS-SECTION*
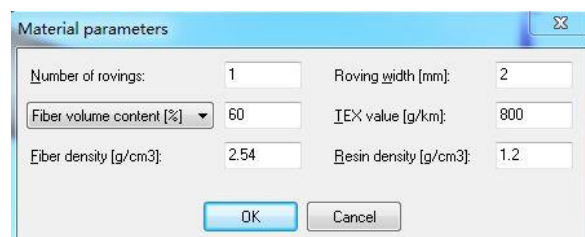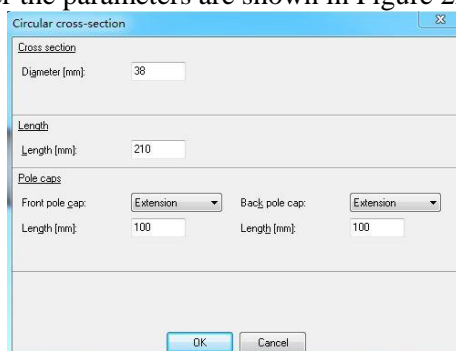2. Enter the parameters are shown in Figure 22.

Figure 22: Mandrel geometries with circular   Figure 23: Material parameters setting cross-section

Step 2: Winding process
Choose *WINDING/SELECTION* from the menu, selection non-geodesic parameters are present in Figure 23

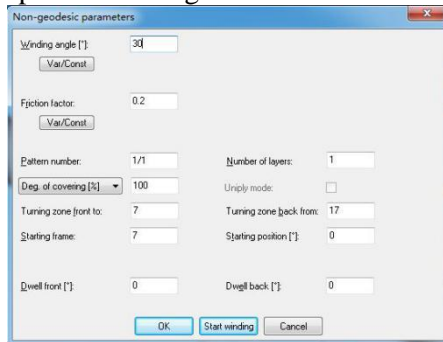Step 3: Choose *WINDING/NON-GEODESIC PATTERN* from the menu, enter the following parameters are provided in Figure 24
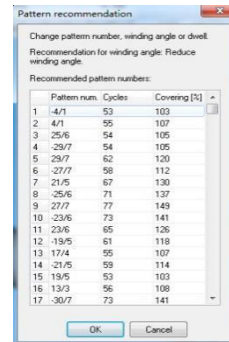

Figure 24: Non-geodesic parameters setting   Figure 25: Pattern recommendation

Then click on "Start winding", the program calculates the winding pattern according to the entered winding and material parameters. About pattern number, system default parameter is 1. Based on different setting values, pattern number can be calculated by the software itself, which can select a proper pattern number is noted in Figure 25.The first fibre trajectory is visible, the complete laminate will be wound on the mandrel.

4.3 30°, 45°, and 60° winding angle filament wound cylinders simulation

Based on the above the working principle of CADWIND software, it is sufficient to perform different winding angle simulation to check and compare with 3 axes filament winding machine experiment products. This simulation will cover 30°, 45°and 60°three different type winding angles, which will fabricate the tubular products with 210mm length and 38 mm inner diameter.

4.3.1 Simulation with 30° winding angle

Simulation parameters have been shown in Table 4, which is the related setting for 30° winding angle. Figure 26 illustrates the 30° winding angle tubular specimen with the isometric view. Figure 27 is the front view of 30° winding angle tubular specimen, which is clear to observe the fibre path, repeated pattern, and coverage.

Table 4: 30° winding angle tubular specimen details

Core model size/mm			Winding angle/°	Fiber bandwidth/mm	Friction coefficient	Remark
Diameter	Winding length	Extension length				
38	210	100	30	2	0.2	

Note: Winding length refers to the length of the fiber covered area with a 30 degree winding angle

Extension length refers to the fiber on mandrel with 30 degree winding angle, which coverage beyond the ends of the length. It can provide adequate space for changing fiber direction.
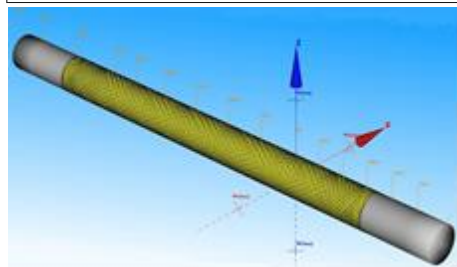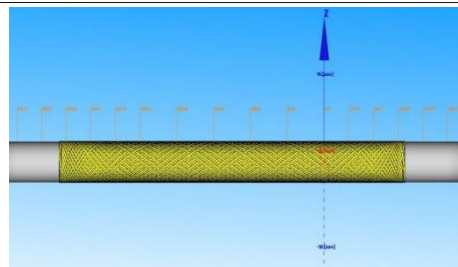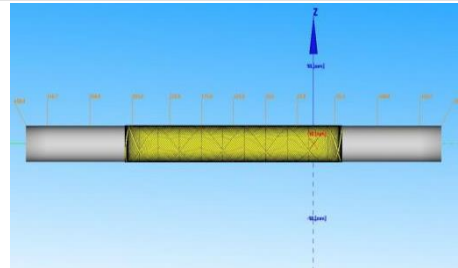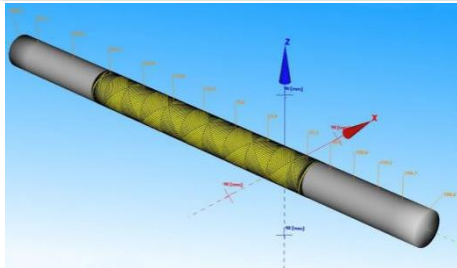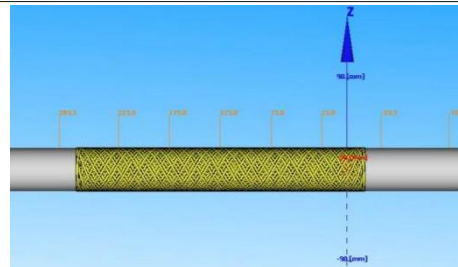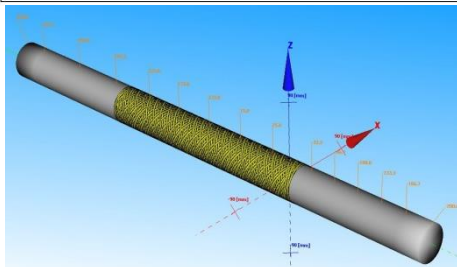

Figure 26: 30° winding angle tubular specimen   Figure 27: 30° winding angle tubular specimen
with the isometric view   with the front view

4.3.2 Simulation with 45° winding angle

45 ° winding angle simulation parameters have been presented in Table 5, which is the vital setting for 45 ° winding angle. Figure 28 illustrates the 45 ° winding angle tubular specimen with an isometric view. Figure 29 is the front view of 45 ° winding angle tubular specimen, which can have a brief observation on fibre path, repeated characteristic pattern, and coverage.

Table 5: 45 ° winding angle tubular specimen details

Core model size/mm			Winding angle/°	Fiber bandwidth/mm	Friction coefficient	Remark
Diameter	Winding length	Extension length				
38	210	100	45	2	0.2	
Note: Winding length refers to the length of the fiber covered area with a 30 degree winding angle						
Extension length refers to the fiber on mandrel with 30 degree winding angle, which coverage beyond the ends of						
the length. It can provide adequate space for changing fiber direction.						

Figure 28: 45 ° winding angle tubular specimen with the isometric view

Figure 29: 45 ° winding angle tubular specimen with front view

4.3.3 Simulation with 60 winding angle

60 ° winding angle simulation parameters have been provided in Table 6, which supplies setting values for 60 ° winding angle. Figure 30 illustrates the 60 ° winding angle tubular specimen with an isometric view. Figure 31 is the front view of 60 ° winding angle tubular specimen, which can have an accurate view of fibre path, repeated characteristic pattern, and coverage.

Table 6: 60 ° winding angle tubular specimen details

Core model size/mm			Winding angle/°	Fiber bandwidth/mm	Friction coefficient	Remark
Diameter	Winding length	Extension length				
38	210	100	60	2	0.2	
Note: Winding length refers to the length of the fiber covered area with a 30 degree winding angle						
Extension length refers to the fiber on mandrel with 30 degree winding angle, which coverage beyond the ends of						
the length. It can provide adequate space for changing fiber direction.						

Figure 30: 60 ° winding angle tubular specimen with isometric view

Figure 31: 60 ° winding angle tubular specimen with with front view

5. Experiment and CADWIND software simulation comparison

In comparison with the 3-axis filament winding machine experiment and CADWIND software simulation, which refer to filament winding process level, mandrel coverage rate, repeated

characteristic pattern, the change degree of specimen shape, specimen surface smoothness, turnaround impact and other parameters. Experiment products and simulation specimen photos are shown in Table 7. The comparison results are presented in Table 8.

Table 7: Experiment and simulation winding pattern view

Table 8: Comparison specification results

Comparison specification	Experiment process	Simulation process
Filament winding process level	High	High
Mandrel coverage rate	75%—85%	100%(controlled)
Repeated characteristic pattern	One pattern	More than two patterns
Degree of specimen shape change	15%—24%	Less 5%
Specimen surface smoothness	Moderate-High	High
Turnaround impact	High	Low
Machine axes	3 axes	4 axes
Friction impact	Unstable value	Constant value
Process error	＜15%	1—2%
Control system code	Calculation and write	Generate automatically
Process time	Long time (based on filament winding angle)	Short time
Fibre slippage impact	Low-Moderate	No effects
Winding angle accuracy	Moderate-High	High
Control system	Arduino UNO and CNC shield	CNC control system

Experiment and simulation results can present more ideas on the 3-axis filament winding machine and CADWIND software. As for the 3 axes filament winding machine, the machine can provide a good winding pattern with high winding angle. The low winding angle can appear more voids, which can be modified by filament winding codes. The turnaround zones on both sides can cause friction, which can affect the winding angle. This problem obviously happened on 30 winding angle. In the real winding process, the turnaround zone needs to take into consideration on effect on winding angle. The machine also can reduce the fibre slippage through lower the process speed. In short, the 3-axis filament machine can wind as the winding codes, but it needs to improve winding condition. As for the CADWIND software, it is the sufficient and reliable software to simulate winding condition. Software function is trying to simulate the real winding condition as close as

possible. The fibre tow thickness and turnaround zones issues need to exploit and add in this software, which can complete the software function and simulation results. There is no doubt that CADWIND software is efficient in filament winding technique field, which can meet general requirements for winding parameters.

6. Conclusion and recommendation

6.1 Conclusion

The 3-axis filament winding machine has been successfully designed and fabricated, which can have a sufficient processing capacity to produce certain composite material products. Based on the experiment and simulation results, the machine provides a good filament winding process and a moderate filament wound composite cylinders. This 3-axis filament winding machine can evaluate its capability from machine structure and control system perspectives. In terms of machine design structure, it can meet the requirements in mandrel rotation and carriage unit movement. In control system perspective, it can simply control the machine using UGS software with an inexpensive control system. But this 3-axis filament winding machine still needs further improvements before selecting it as final machine development to fabricate filament wound composite cylinders for the compression test. It also provides the development and optimization orientation about the machine from comparison results.

6.2 Recommendation

It is suggested that the following improvements of the 3-axis filament winding machine should be carried out afterward:

a) Improvement of UGS codes

The current machine carriage unit changes the direction in turnaround zone, which needs to have one more round to rotate. It can effectively reduce the fibre slippage movement. But on the other hand, it will waste much extra fibre and resin. To remove one more round in the turnaround zone, it needs another available way to deal with fibre slippage especially in 30 ° filament winding angle process.

b) Control the fibre tension and friction

During the filament winding machine process, a certain fibre tension should be provided with tension device or manual in experiments. The friction force mainly affects the filament winding products with the certain winding angle on the mandrel surface. It should be calculated and tested in the future, which can improve the filament winding angle accuracy.

c) Control system replacement

This machine is controlled by Arduino UNO and CNC shield with low costs and inexpensive control system characteristic. However, it has limitations about the control system. The upload related G-code is limited to support the format, which cannot write more general type of C-codes to control the machine. It is better to use PLC control system to replace it, which can separate control each axis rotation and movement. It is quite convenient to test and perform different mandrel shape.

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