



Manufacturing and Pressure Characteristics of CFRP Pipe Produced with Filament Winding Method

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Abstract. This research was conducted by designing and modifying the composite prepregs-making machine developed in the previous research, in order to capable of adjusting the angle of fiber winding during the filament winding process. Composite pipe samples were produced using reinforcing fibers, namely carbon fibers, impregnated with a polymer matrix of epoxy resin and epoxy hardener. The tested variations of winding angles included angles of $[90^\circ]_6$, $[\pm 30^\circ]_3$, $[\pm 45^\circ]_3$ with respect to the longitudinal axis of the pipe, as well as combinations of these angles. Axial compression testing was performed to measure the mechanical response of the pipe to compressive loads, specifically how the material absorbs energy during deformation or fracture. Parameters analyzed in this research included peak load, average load, crush load efficiency, and energy absorption. The test results revealed that composite pipes with a combination of winding angles had the highest peak load value and the greatest energy absorption. Although peak load and absorbed energy tend to decrease with increasing winding angle orientation, the crush load efficiency increased with higher winding angle orientations. From the findings of this study, it can be concluded that composite pipes using a combination pattern of helical winding and hoop winding layers are capable of producing optimal mechanical properties that cannot be achieved with a single fiber orientation.

Keywords: Filament Winding, Helical Winding, Hoop Winding, Energy Absorption, Composite.

1 INTRODUCTION

Composite materials are considered as alternatives to conventional materials by engineers and designers when selecting materials for applications where the weight-to-strength ratio is a significant parameter. These materials have been widely used in various sectors, including defense, aerospace, sports, as well as pipes and pressure vessels in the chemical industry [1]. Composite is a material that is formed from a mixture of two or more constituent materials through a mixture that is not homogeneous and has different mechanical properties from each constituent material. Reinforcement in composites can take the form of dispersed particles or fibers [2].

Due to the importance of weight reduction and cost savings in today's industry, the primary goal of manufacturing processes and techniques is to integrate automation into the manufacturing techniques used to produce advanced composite structures. Among

winding is one of the most cost-effective methods. Filament winding is a process where fibers are accurately placed in predetermined orientations on a mandrel to form the final component. Desired composite thickness and geometric strength can be achieved by varying parameters such as (a) winding tension, (b) winding angle, and (c) resin content in each layer of reinforcing fibers [3]. There are three basic winding patterns used: (i) Hoop Winding, (ii) Helical Winding, and (iii) Polar Winding [4]. The properties of the final components depend on the chosen winding pattern during the fabrication process.

The technique of filament winding started to develop in the 1950s, involving controlling the two necessary rotational axes [5]. In the 1970s, the use of servo controls simplified this task, and now, with the rapid advancement in computational systems, sensing, and control, sophisticated filament winding machines controlled by computers are available. This advanced technology is employed to produce symmetrical advanced profiles, ultimately enhancing the final equipment costs. Therefore, this research focuses on the filament winding manufacturing method using previously designed machine and compares the composite strength based on the applied winding angles namely, 90°, 30°, 45°, and combinations, through axial compression testing.

2 THE FILAMENT WINDING MACHINE

Purba [6], designed and built a prepreg molding machine. This machine is divided into four parts: the machine frame, resin box, mandrel shaft system, and the electric motor along with its control system. The constructed machine has dimensions of 1040mm x 750mm x 609mm. The design process involved calculating shear, compression, and tensile strength on the components used in the machine. Strength calculations were performed on the machine. Design modifications can occur if the fiber winding process cannot proceed smoothly. The manufacturing of this machine was carried out through several stages, including machine design, component manufacturing and assembly, electronic circuit installation, calibration of the electric motor using Mach3Mill software, generating G code to control the machine, and testing the machine to produce prepreg. The machine design process was initiated by creating a 3D machine design. The 3D design was executed using Autodesk Inventor 2020 software. During this phase, the machine was designed to meet the specified requirements. The design process included designing the frame, mandrel and shaft, bearing selection, electric motor determination, chain and sprocket determination, sprocket hub design, as well as strength calculations. The strength calculations for the frame and other parts were conducted to ensure the machine could adequately withstand the load during operation. The machine design was proven to have machine's capability to produce composite prepreg sheets. The machine shown in Figure 1.

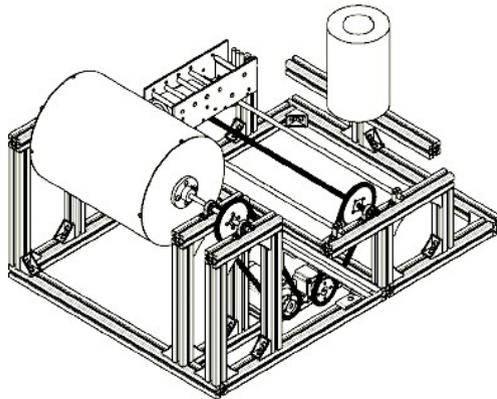


Fig. 1. The unidirectional prepregs Machine [6]

The prepregs sheet was produced using hoop winding only. For the purpose of making composite pipe with various fiber orientation, the machine need to be modified by adding some computer control command. The filament feeder also should be modified in order to make possible to feed fiber in various orientation. The modification of computer command involving G-code command to move the resin carrier back and forth.

3 EXPERIMENTAL METHOD

The initial stage of this research involves the introduction to the prepreg manufacturing machine previously designed and constructed by Purba, Daniel [6]. This machine is then modified with the aim of producing composite pipes with winding angle variations, including 30° , 45° , 90° , and combinations of these angles. After the modification stage, the next step is the process of generating G-code. This section is crucial as the creation of G-code will control the formation of winding angles with different variations.

Once the machine is assembled and modified, a performance test is conducted to ensure that the machine meets the desired criteria. In this testing phase, the primary focus is on the generated G-code and the precision of fiber placement on the mandrel. After the testing is completed, the production of composite pipes can commence, producing composite pipes with varying angles of winding. To produce composite pipes with a combination of winding angles, the rolling process is carried out with 3 different angle variations. The rolling arrangement is for the first layer using a winding angle of 90° back and forth, then for the second layer using a winding angle of 45° back and forth, for the third layer using a winding angle of 30° back and forth, and for the last layer to cover the composite pipe using a winding angle of 90° . The pipe then cut to dimension as shown in Figure 2.

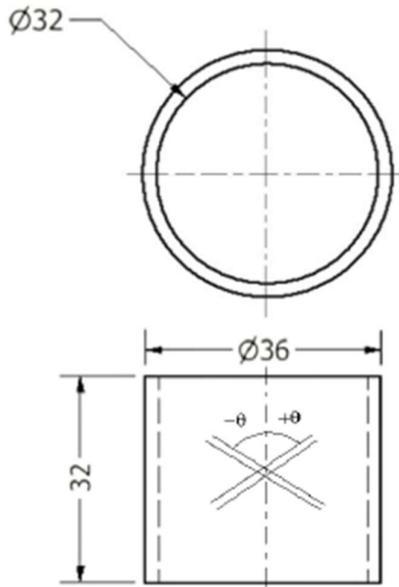


Fig. 2. The specimen dimension and fiber direction.

Subsequently, the produced composite pipes are tested using an axial compression testing method with the use of a universal testing machine of Carson model CRN-50, with a maximum capacity of 50kN. The purpose of this testing is to assess the compressive strength of the material and compare it. The testing involves measuring the maximum load point, average load, and total energy absorbed by the composite pipes produced. This testing method follows ASTM D695 standards, in which the composite samples undergo axial compression tests along the main axis of the cylinder [7],[8].

The testing is performed using the CRN-50 model universal testing machine, where the top and bottom pressing plates move downward at a rate of 1 mm/minute along the axial direction. The upper and lower pressing plates are aligned to evenly distribute force onto the surface of the cut samples. Data in the form of displacement-force curves are recorded through force and displacement measurement devices.

The number of samples tested for each winding angle variation is 5 samples, making a total of 20 tested samples. To calculate the total absorbed energy, the area under the displacement-load curve is calculated. The collected data is then processed and analyzed to understand the mechanical properties of the material with different variations of winding angles. Analyzed parameters include the volume fraction of composite pipe, peak load point, average load, crushing load efficiency, and total absorbed energy. Table 1 shows the specimens tested in this research.

Table 1. Specimen fiber orientation and dimension.

Specimen Code	Fiber Orientation (θ)	Length (mm)	Inside Diameter (mm)	Thickness (mm)	Mass (gram)
901 to 905	[90]5	32 ± 1	32	2 ± 0.05	10.9
301 to 305	[±30]3	32 ± 1	32	2 ± 0.05	8.68
451 to 455	[±45]3	32 ± 1	32	2 ± 0.05	9.97
C1 to C5	[90/±30/±45/90]	32 ± 1	32	2 ± 0.05	9.4

Volume fraction is the ratio between the volume of fibers and the total volume of the composite. According to Daniel [7], volume fraction of the specimen was measured and calculated based of the equation (1).

$$V_f = \frac{v_f}{v_c} \times 100 = \frac{v_f}{(v_m + v_f)} \times 100 \tag{1}$$

Crush load efficiency is the percentage ratio of the average load and the initial peak load, which is a useful index for evaluating the stability of the material crushing process and the crush load efficiency is calculated by [9].

$$\eta_f = \frac{P_{peak}}{P_{mean}} \times 100 \tag{2}$$

Energy Absorption is the energy dissipated by the absorber during a collision. The absorber absorbs impact energy through mechanisms of plastic deformation and failure. The area under the force-displacement curve is defined as the work done by the absorber [9]. Energy absorption is calculated using the formula:

$$E = \int_0^{\delta x} f(x) dx \tag{3}$$

4 RESULTS AND DISCUSSIONS

4.1 Lumped Capacitance Calculation Results

The resulting composite pipes still exhibit a few shortcomings, namely an inability to achieve a perfectly even pipe surface and the presence of porosity at certain points. This is due to the absence of a perfected curing process method. The current machine also lacks the capacity to produce composite materials with various fiber variations; currently, it can only generate composite materials using carbon fibers.

The composite pipe manufacturing machine utilizing the 2-axis filament winding method still harbors some limitations. These include the impact of the turnaround zone leading to material wastage, precision levels not reaching the standards of 4-axis or more machines, low fiber volume fractions in the produced output, and a relatively lengthy production duration.

In the axial compression testing process, all specimens with a specimen length of 32 mm were compressed to 22.5 mm (approximately 70.2% step efficiency) for axial crushing at a displacement rate of 1 mm/minute. Documentation was carried out at each displacement of 0 mm, 5 mm, 10 mm, and 20 mm, which can be observed in Figure 3. The axial crushing process for 90° angle composite pipes is a type of progressive failure which may also be seen in figure 3 where the collapse is at the end of the pipe.

Progressive failure refers to a situation where failure starts from one particular point or part and then spreads slowly or progressively to other areas of the material or structure. Progressive failure involves the gradual propagation of damage through the end of the composite as the load continues. Composite pipes with winding angles of 45° and 30° experience a type of catastrophic failure where the destruction occurs very suddenly or quickly which can be seen in the curve where the decrease when the peak load has reached, the load decreases drastically.

The data collected and processed in this study includes load and displacement data. From this axial compression testing, it was able to determine the strength comparison of each tested angle variation and also understand the mechanical properties of the produced composite pipes. Each variation exhibits distinct crushing characteristics showed that the decrease in orientation angle resulted with inner and outer irregular splaying behaviors of the fibers and intensifying of fronds, as seen in Figure 4. It can be seen from this figure, that the crushed specimen shows different mode at the difference fiber orientation. The 90° deg specimen shows fiber breakage, while the other angle shows the combination of fiber breakage and interlaminar shear failure.

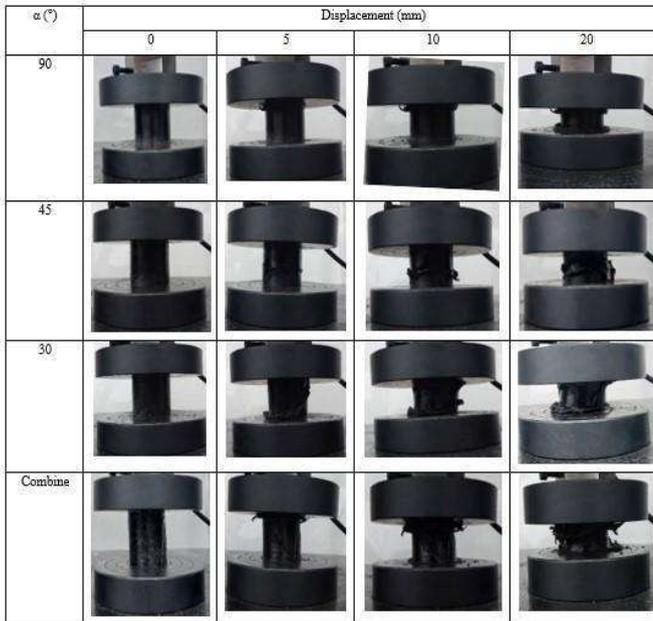


Fig. 3. Compression step of each specimen.

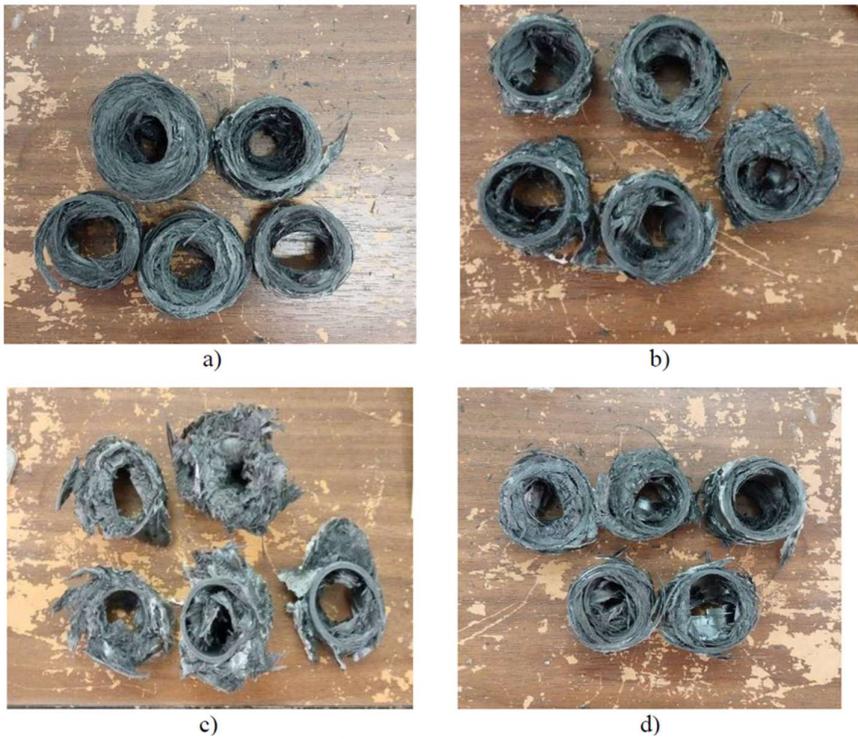


Fig. 4. The Spesimen after tested a) 90° b) 45° c) 30° d) Combination.

Table 2. The calculated Efficiency and Energy absorbed.

θ (°)	m (g)	Vf (%)	P_{peak} (kN)	P_{mean} (kN)	η_f (%)	E (J)
90	10.8	39.3	9.632	7.763	80.6	68.044
45	9.5	37.4	13.749	9.85	71.6	84.55
30	8.4	34.3	15.474	9.477	61.3	91.442
Combination	9.3	36.6	16.058	12.034	74.9	97.954

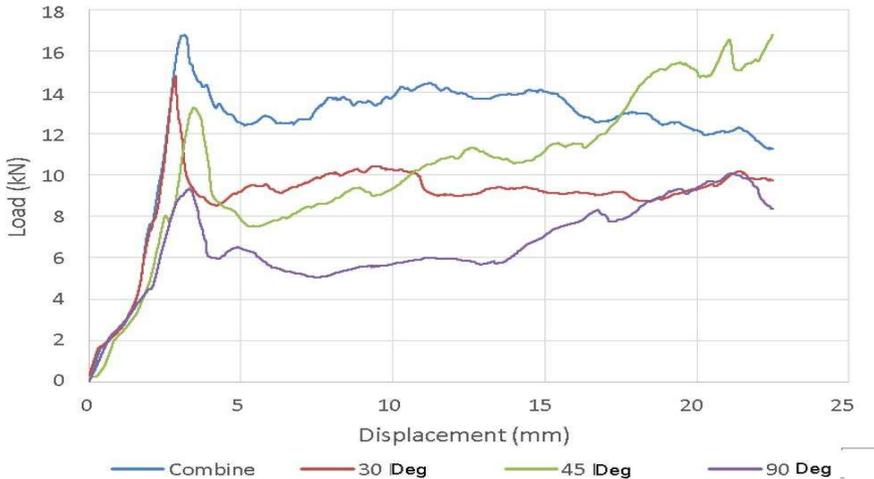


Fig. 5. Load-displacement curve of the Spesimen after tested.

In Figure 5, the load-displacement curve was attained directly from the testing machine. From the figure, the area under the displacement-load curve can be calculated, where this value represents the absorbed energy during the compaction phase. In this study, energy absorption is calculated up to a displacement of 10 mm. The calculation results indicate that the composite pipe with a combination of angles has the highest energy absorption value, followed by angles of 30°, 45°, and 90°. This is consistent with findings from a study conducted by Ma Quanjin [1] and Ozbek, Ozkan [8], where one of their conclusions is that increasing the fiber orientation angle leads to a decrease in energy absorption. The comparison of energy absorption magnitudes for each variation can be seen in Table 2. The crush load efficiency of the four variations of composite pipes produced was calculated using equation (2). The calculation of crush load efficiency was done by comparing P_{mean} with P_{load} . Data and calculation results for the sought crash safety parameters can be seen in Table 2.

5 CONCLUSION

The constructed machine has dimensions of 1040mm x 750mm x 609mm. This machine operates in two motion axes, where the X-axis represents the movement of the resin box, and the Y-axis corresponds to the mandrel rotation direction. The built machine utilizes Mach3mill software as the control system for inputting G-code. It is capable of producing composite pipes with hoop winding and helical winding patterns, featuring various angles of winding direction, yet with certain observations.

In the axial compression testing, composite pipes with combined layer variations showcase remarkable mechanical properties. These pipes exhibit the highest peak load and energy absorption values and possess a good crush load efficiency. This outcome is a combination of the properties of helical winding patterns, which yield high peak load and energy absorption values, and hoop winding patterns, which exhibit favorable crush load efficiency. Consequently, layering combinations in filament winding can

create materials with optimal mechanical properties and structures that cannot be achieved with a single fiber orientation. This helps optimize mechanical strength according to the desired design and specifications. However, it's important to note that such a more complex design might require extra efforts in production and validation processes to ensure that the pipes meet desired specifications and requirements.

From the data and graphs derived from the axial compression testing, it can be concluded that larger winding orientation angles correlate inversely with peak load and energy absorption values. For smaller angles, interlaminar cracks propagate easily along the longitudinal axis, forming longer crack lengths. This results in more extensive damage fragments and also leads to decreased crush load efficiency.

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