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Enhancing the Mechanical and Dielectric Strength of Glass Fiber Composites: A Filament Winding Process Study

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Abstract:
This research aims at establishing how the filament winding method can be employed to enhance the mechanical and dielectric characteristics of glass fibre reinforced composites. These are materials which have properties above the constituent parts of fibers and matrix, and fibers and a matrix consolidate to make them. Since the level of dielectric strength and flexural bending stress depends on such parameters as winding angle, the number of layers, and winding speed, this study examines these factors systematically. The significance of each of these factors and their optimal combination is identified in this study by means of regression analysis and Taguchi design L9 array. The results are depicted as containing effects of significance as well as adding knowledge in regards to measures of the composite needed alterations in winding angle, number of layers, and winding speed. This generates effective guidelines for developing premium quality glass fiber composite materials and enhances the knowledge of the composite behaviour. In conclusion, the findings captures the essence of how parameter optimization is crucial to the determination of desired properties of the developed materials and bring about development of composites for use in areas that require both mechanical and electrical strength as well as electrical insulation.

Keywords: Mechanical properties, dielectric properties, Composite materials, Filament winding process, Optimization.

1. Introduction

Composite materials are materials made from two or more materials all integrated together. In the reality that cannot be achieved with fiber or with matrix when these serve as the only component (Bhanuprakash et al., 2022). Fiber as well as the matrix material have their parameter of properties to be selected with regard to application. The Matrix material holds the fibers together and distribute the loads, stress between the fibers (Tehami et al., 2017). The maximum operating temperature of the material is decided by Matrix. Generally, there are two kinds of matrix materials: As mentioned above we have the thermoplastics and thermosets. These are selected based on the apparent need to meet the glass transition temperature Glass transition temperature refers to the temperature at which, polymer changes its physical properties from that of a hard and brittle material to a flexible rubber like material (Maries & Abrudan, 2018).
The engineering applications of Glass fiber reinforced polymer (GFRP) composites are many and include the following. The mechanical characteristics of the reinforced composites are a function of the fiber strength and young's modulus, the stability, and the matrix strength for the respective composite. Desired characteristics and functional properties of GFRP composites were made enough to compete with steel by directing orientations and composition of glass fibers Properly, it was stiffer as compared to aluminum and had less relative density as compared to steel (Kumar et al., 2017).
In the electrical industry application, modulus of elasticity (Flexural modulus) and short time dielectric strength are more important for the functional or application rather than the Dielectric strength (Chaudhary & Ingole, 2020). The technique of measuring the flexural modulus includes volume extraction method, three point bending test and the tensile testing. In this paper the typical mechanical characteristic of the glass fiber material with the filament winding, vacuum impregnation method put in to practice will be described. The given information will provide the contrast between both the processes (Chaudhary et al., 2018.
The investigation of Flexural bending stress on composites as well as dielectric strength of the substrate will also form the basis of this study. The outcomes would be useful for establishing high-performance insulating tubes within the next-generation high-voltage circuit breakers (Zhang et al., 2022).

2. Material and Manufacturing Methods

The Material selected for the presented study is Insulating tube which is used in electrical industry & is produced by different process and with glass fiber material. The Insulating tube is normally manufactured by vacuum impregnation technique & Filament winding technique (Insulating materials- electrial, 2021). As to an extent the content of the material where we find the type of reinforcement and fiber inside the chemical composition and mechanical properties found are based on this factor. The composite material we are going to design is orthotropic material and young modulus property will change with direction (Tiwari et al., 2021.

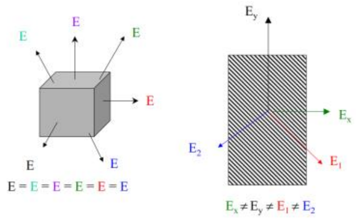

Fig. 1: Isotropic Vs Orthotropic material

2.1 Glass Fiber-reinforced polymer composites

In this composite consist of a polymer resin material as a matrix and having the glass fibers as the reinforcement medium. This type of material utilized in the highest degree of the varieties of the applications (nandaragi et al., 2018). The diameter of the fibers results in a range between 3- 20 microns. Glass fiber is the preferable fiber material from the points of view of easily dra. Out of all synthetic fibers, glass fibers are widely used due to their high strength and durability, thermal conductors, impact, chemical, friction, & wear. But when working on common machining systems, the machining of glass fibers is relatively slow, difficult and also reflects low tool durability (Design and Analysis of S-Glass/Epoxy Composite Mono leaf Spring for Light Vehicle, 2017).

2.2 Filament Winding Process

Filament winding process is extensively used for the construction of the open & closed end cylinder like parts pressure vessel or tank etc. In this process the filament under tension is wound around a rotating mandrel (Abdalla et al., 2007). The mandrel only rotates around the spindle while the carriage move in the horizontal direction parallel to the rotating axis of the mandrel. There are two most common filaments used in making of the composite, they being glass and carbon. Fibers that got soaked in the resin bath and wrapped on the mandrel can be described as follows (Ding, 2019). On mandrel covering achieving the desired thickness, the resin is set, whiles finishing of the product is done. For the curing purpose, the mandrel is taken on an oven or alternatively heating means are provided on which the mandrel is kept until the component is cured. In the process from the resin curing the mandrel will be extracted and the s described product will be hollow. Also, the process offers the high strength to weight ratio of the insulating tube and procures the high degree of the control on uniformity and fiber orientation (Gorthala et al., 1994).

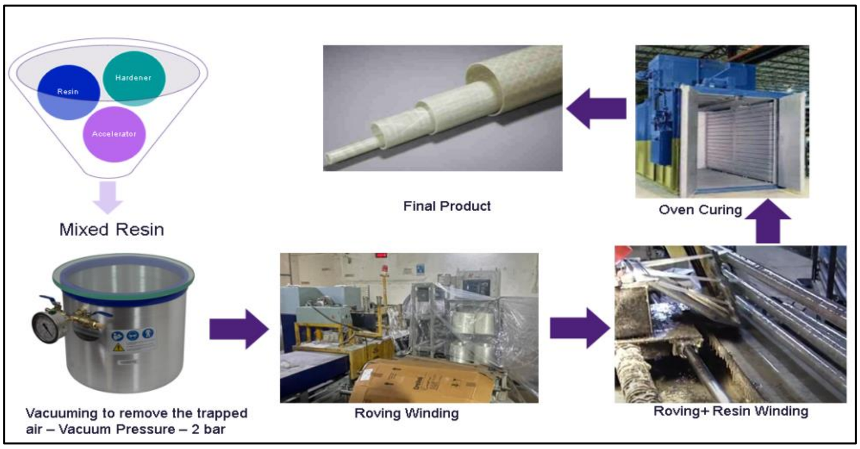

Fig. 2: Schematic Filament winding process

2.3 Methods for Evaluation of Dielectric Strength

a) Dielectric Strength

The setup was designed to check the axial dielectric strength of the composite material. It consists of extension housing, bushing, Electrode, Tank cover and NRV (Non return valve). The NRV was using to fill the dielectric gas inside the extension housing. The test specimen will be placed inside the two electrodes. With the help of spring and spring guide the sufficient pressure was applied on the specimen to hold the electrode during the voltage application. The electrode was made of Aluminium alloy material with proper radiuses to withstand the dielectric stresses generated during the test.

The complete the dielectric test setup was placed on voltage generator to apply the voltage across the electrodes. The voltage is applied between the electrodes in step manner and put for the 1min. voltage withstand. After that the voltage will be increased and check for the breakdown voltage. The dielectric strength will calculate by dividing the breakdown voltage to distance between the two electrodes.

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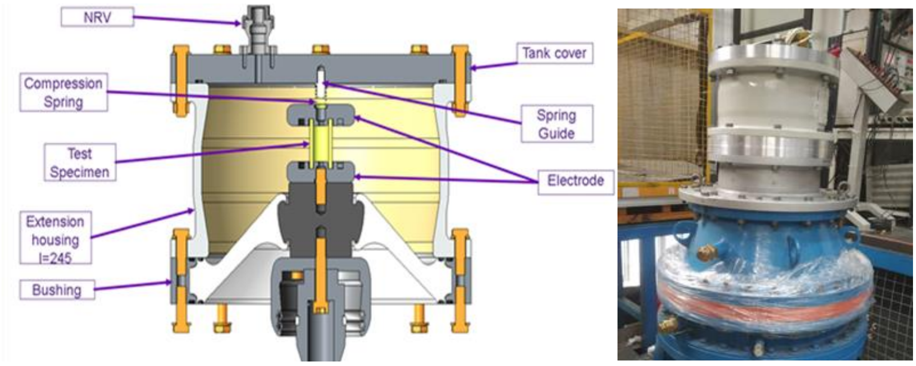

Fig. 3: Dielectric Strength testing setup

b) Sample Test Specimen for Dielectric Testing

The sample test specimen used for dielectric testing was a cylindrical tube with an outer diameter of 36 mm, an inner diameter of 24 mm, and a length of 100 mm.

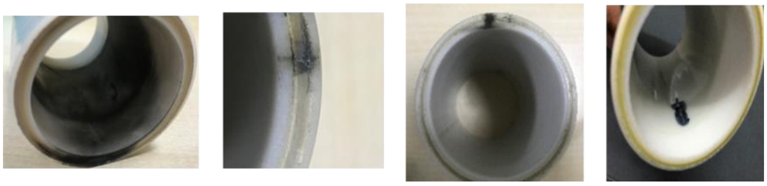

Fig. 4: Dielectric sample is prepared and tested on setup

Fig. 5: Dielectric Strength Tested sample

2.4 Methods for evaluation of flexural strength

a) Flexural Strength

The beam is a tube specimen and is pinned close to the ends. To the carrying out of the three-point bending test, the beam is loaded at the middle of its length. As there are three significant regions (two supports at ends and one loading point) over the length of the beam this technique is known as three-point bending test.(Green Mechanic: Bending Moment in a Beam Lab Report, 2017)

In this test a specimen with tube section is placed on two parallel supporting 'Pins'. This loading force is applied in the middle by the use of what are commonly known as loading jaws. The supporting pin and loading jaws are arranged in such a manner that they are rotation about an axis lying in the plane of the pin axis and the specimen axis (Wang et al., 2018).

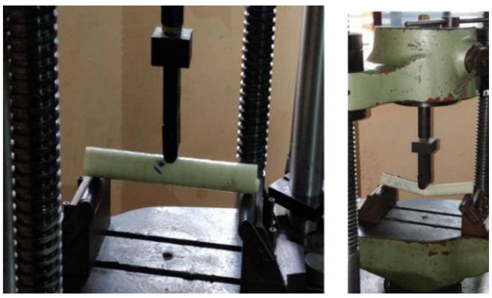

Fig. 6: Schematic of the Three-point bending test

b) Sample Test Specimen for Flexural Strength

ASTM Standard: The testing procedure followed the ASTM D790-17 standard, which outlines the test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials.

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The sample test specimen used for flexural strength testing was a cylindrical tube with an outer diameter of 36mm, an inner diameter of 24 mm, and a length of 200 mm.

Fig.7: Flexural Strength Tested sample

3. Results and Discussions

Minitab statistical software has been used for this purpose. Models have been made of the modulus strength and dielectric strength. ANOVA has been used to find out how each parameter affects the modulus strength, dielectric strength and a linear regression model has been made to predict output model.

3.1 Calculation of SN ratio

SN ration is used to normalize the experimental data in specific range calculated and the response for SN ratio smaller is better selected.
Given below is the equation of Signal-Noise (S/N) ratio for the response
$S/N = -10\log_{10}\sum\frac{y2}{n}$
Where y is the response value and n is the number of total experiments.
Similarly, Signal to Noise ratio values can be obtained for other experimental runs in orthogonal array. The Cumulative data for S/N ratio glass fibre epoxy resins composite of modulus strength, dielectric strength are calculated as shown in table 2.

Table: 1 L9 Signal to Noise Ratio of modulus strength, dielectric strength

Experiments	Inputs Factors			Mechanical properties		Dielectric properties	
Trial No.	Winding Angle (Degree)	Number of layers(No's)	Winding Speed (m/min)	Flexural Bending Stress (MPa)	S/N Ratio	Dielectric Strength (Kv/mm)	S/N Ratio
Sample 1	30°	4	8	233.89	47.3802	7.98	18.0401
Sample 2	30°	5	10	225.89	47.0779	7.56	17.5704
Sample 3	30°	6	12	231.20	47.2798	8.06	18.1267
Sample 4	45°	4	10	238.77	47.5596	8.16	18.2338
Sample 5	45°	5	12	240.11	47.6082	7.17	17.1104
Sample 6	45°	6	8	231.77	47.3011	7.58	17.5934
Sample 7	60°	4	12	236.57	47.4792	8.24	18.3185
Sample 8	60°	5	8	226.44	47.0991	7.36	17.3376
Sample 9	60°	6	10	219.89	46.8441	8.44	18.5268

With the help of the Minitab 19 software, the values of the S/N ratio are found. All of the experiments show that there isn't much difference in the S/N ratio.

3.2 Main Effects Flexural Bending Stress and Dielectric Strength

- Graph 1 shows the main effects plot from S/N ratios.

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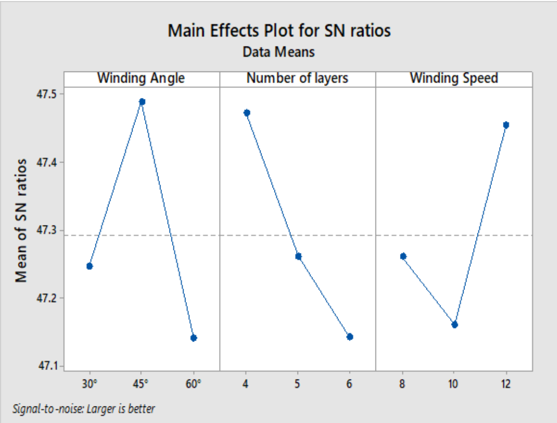
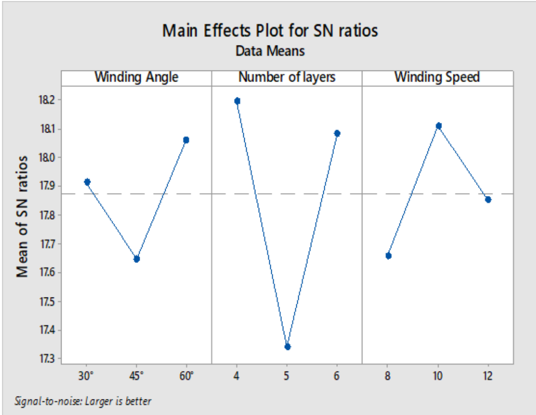


Graph: 1 Main Effects Plot for flexural bending stress



Graph*: 2 Main Effects Plot for dielectric strength*

- High S/N ratio: Indicates that the signal is much stronger than the noise. A high SNR is generally desired as it means that the quality of the signal is good and less likely to be distorted by noise.
- Low S/N ratio: Indicates that the signal is weaker compared to the noise. A low S/N ratio means that the noise is more prominent and can obscure or distort the signal.

From Graph 1, the Main Effect plot for the S/N ratio of glass fibre polymer composite for flexural bending stress optimally measured response is the level of a factor that has the highest SN ratio. The optimal flexural bending stress parameters were 45° winding angle (level 2), 4 number of layer (level 1) and 12 m/min winding speed (level 3).
From Graph 2, the Main Effect plot for the S/N ratio of glass fibre polymer composite for dielectric strength optimally measured response is the level of a factor that has the highest SN ratio. The optimal dielectric strength parameters were 60° winding angle (level 3), 4 number of layer (level 1) and 10 m/min winding speed (level 2).

3.3 Analysis of Variance

ANOVA is a statistical method for figuring out how well a number of different variables fit together. With a confidence level of 95%, or P values of less than 0.05, the results were found. It also shows how much each element contributed and how much it changed, which shows which factor had the biggest effect on the result.
fLN = N-1 gives the number of degrees of freedom as a whole.
Here's how to figure out degrees of freedom for residual error:
DF= (fLN) – (Sum of DF of all the terms included in the model)
In this study, a standard L9 array with three levels and four parameters is used. In this study, the winding angle, the number of layers, the winding speed are the three process parameters those were chosen.
Total fLN degrees = N-1 = 9-1 = 8
Each parameter has three levels, which means it has two degrees of freedom.
DF for residual error = 8-(2+2+2+2) = 0

Table 2: ANNOVA Result for flexural bending stress

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**% Contribution**
Winding Angle	2	0.192143	0.096072	94.54	0.010	38.55
Number of layers	2	0.168836	0.084418	83.07	0.012	33.88
Winding Speed	2	0.135293	0.067647	66.57	0.015	27.15
Residual Error	2	0.002032	0.001016			
Total	8	0.498305				

- The table shows the ANOVA for glass fibre polymer composite material. The table shows that the Winding Angle (38.55%), Number of layers (33.88%), and Winding Speed (27.15%) have a significant impact on flexural bending stress.
- The ANOVA results indicate that all three independent variables (Winding Angle, Number of Layers, and Winding Speed) significantly influence the flexural bending stress.
- Winding Angle contributes the most to explaining the variation in flexural bending stress, followed closely by Number of Layers and then Winding Speed.

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Table 3: Model summary

S	R-Sq	R-Sq(adj)
0.0319	99.59%	98.37%

- S: Standard error of the estimate is 0.0319, indicating a small average deviation of predicted values from actual values.
- R-Sq (R-Squared): Coefficient of determination is 99.59% indicates high predictability of the dependent variable from the independent variables.
- R-Sq(adj) (Adjusted R-Squared): Adjusted coefficient of determination is 98.37% indicates the adjusted predictability considering the number of predictors in the model.

Table: 4 ANNOVA result for dielectric strength

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**% Contribution**
Winding Angle	2	0.26545	0.26545	28.12	0.034	14.07
Number of layers	2	1.30127	1.30127	137.86	0.007	68.97
Winding Speed	2	0.31033	0.31033	32.88	0.030	16.45
Residual Error	2	0.00944	0.00944			
Total	8	1.88649				

The table shows the ANOVA for glass fibre polymer composite material. The table shows that the Winding Angle (14.07 %), Number of layers (68.97%), and Winding Speed (16.45%) have a significant impact on dielectric strength

Table 5: Model summary

S	R-Sq	R-Sq(adj)
0.0687	99.50%	98.00%

3.4 Development of Regression Model

Minitab is utilized to create a regression model. By substituting the experimental values of the parameters into the regression equation, flexural bending stress and dielectric strength values for all levels of study parameters can be predicted. The correlation between predicted and experimental values of flexural bending stress and dielectric strength is also demonstrated via graphical representation. Using design Minitab software, a mathematical model for winding angle, number of layer and winding speed is calculated and regression analysis is performed to obtain the predicted value of flexural bending stress and dielectric strength.

Regression Equation for flexural bending stress

Flexural Bending Stress = 240.4 - 4.40 [Number of layers] + 1.32 [Winding Speed]

Regression Equation for dielectric strength

Dielectric Strength = 7.63 - 0.050 [Number of layers] + 0.046 [Winding Speed]

Table 6 shows a comparison between the flexural bending stress and dielectric strength measured by three points bending testing and the predicted by a mathematical Regression Equation l equation.

Table: 6 Experimental and Predicted Values

Sr. No.	**Flexural Bending Stress**			**Dielectric Strength**		
	Experimental value	Predicted value	Error %	Experimental value	Predicted value	Error %
1	233.89	233.36	0.23	7.98	7.79	2.44
2	225.89	231.60	2.47	7.56	7.84	3.57
3	231.20	229.84	0.59	8.06	7.88	2.28
4	238.77	236.00	1.17	8.16	7.89	3.42
5	240.11	234.24	2.50	7.17	7.93	4.61
6	231.77	224.56	3.21	7.58	7.69	1.43
7	236.57	238.64	0.87	8.24	7.98	3.26
8	226.44	228.96	1.10	7.36	7.748	5.29
9	219.89	227.20	3.21	8.44	7.79	8.36

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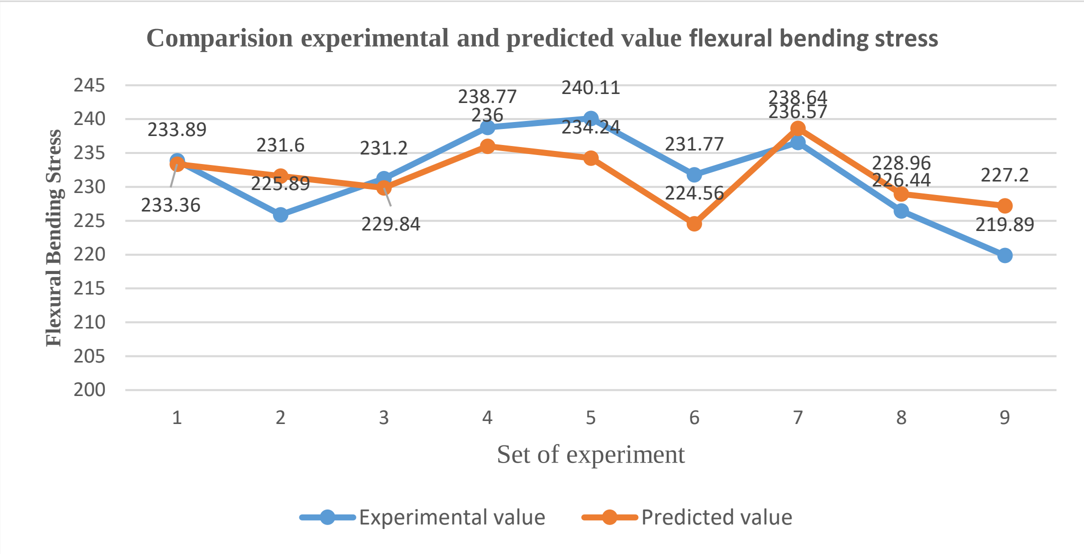
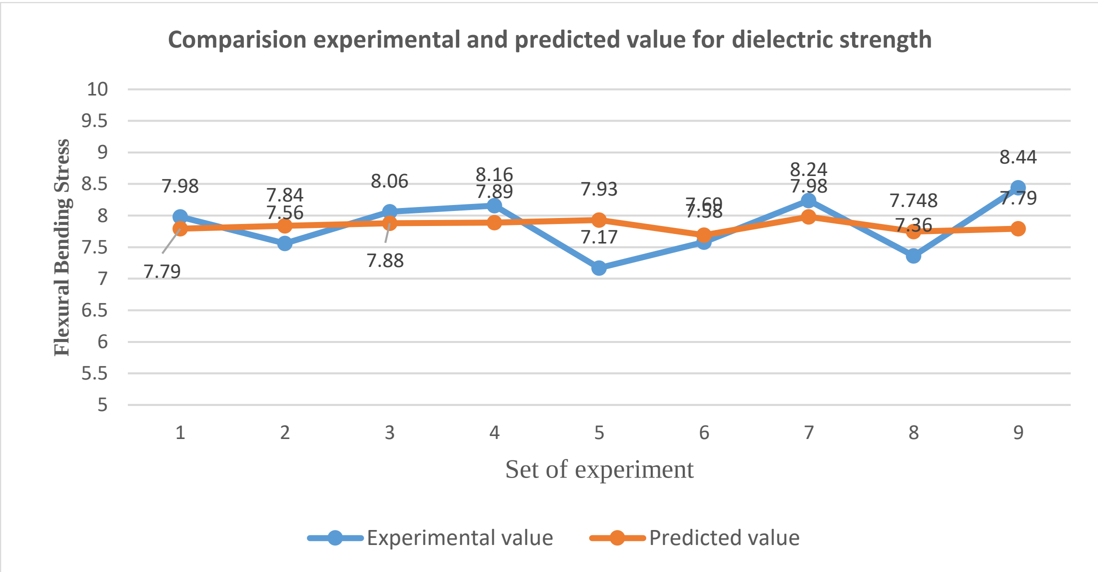
The difference between the calculated values for flexural bending stress and dielectric strength and the experimental values for each experience was found to be less than 10%. We can therefore say that the regression equation that was made is correct. Graph 3 is a picture of the experimental data and the values those were calculated using the regression equation.



Graph: 3 Comparison between Experimental and Predicted value for flexural bending stress

Flexural bending stress increases for the first sample and decreases for the ninth sample. Experiments numbered 1 through 9 comprise the Taguchi design L9 array; each experiment contains a unique mix of parameter levels and various parameter levels.



Graph: 4 Comparison between Experimental and Predicted value for dielectric strength

Flexural bending stress increases for the first sample and decreases for the ninth sample. Experiments numbered 1 through 9 comprise the Taguchi design L9 array; each experiment contains a unique mix of parameter levels and various parameter levels.

3.6 Confirmation of Experiment Result

In Table 7, we can see the difference between the value of the flexural bending stress and dielectric strength from the confirmation experiment and the value predicted by the regression model.

Table: 7 Confirmation Experiment Result

Parameter	Experimental value	Predicted value	Error %
Flexural Bending Stress, MPa	241.8	238.64	1.32
Dielectric Strength Kv/mm	8.48	7.91	7.20

Keeping the parameters at the best levels suggested by the optimization method, a confirmation experiment was done, and the Flexural Bending Stress and Dielectric Strength was compared to what the regression model predicted while keeping the parameters at the same levels. The difference between the actual result and the one that was predicted is 1.32% and 7.20% resp. This shows that the experimental value and the estimated value are similar.

4. Conclusions

- Thus, the research effectively establishes the enhance ability of the mechanical and dielectric properties of glass-fiber composite through a precise control of the filament wound process parameters. This the study revealed that there was a strong evidence that the winding angle, number of layers and winding speed influencing the flexural bending stress and dielectric strength of the composites.
- Further conducted Analysis of Variance (ANOVA) and results indicated that the dependent variables of the experiment flexural bending stress and dielectric strength were significantly affected by the independent variables – the winding angle (38. 55%), Number of layers (33. 88%), and winding speed (27. 15%) for the former while the former is most highly influenced by number of layers (68. 97%), followed by winding speed (The regression models proved higher accountable predictive accuracy through the R-squared results of a 99 percent. 0% for compressive stress on lower surface of the neutral axis, 54% for tensile stress , 42% and 48% for shear stress in the upper and lower flange respectively. 50% for dielectric strength.
- It can therefore be concluded that these parameters if well optimized can result in development of glass fiber composites having the desired characteristics appropriate for different uses in industries.
- The above discussed regression models are well suited to predict those digital properties, as seen in the experimental part where the errors were fairly small. The proposed optimization method has provided the way to synthesise the highly efficient glass fibre reinforced polymer matrix composites with a desirable property for the usage in several industrial applications.

Conflicts of Interest:
The authors declare no conflicts of interest about the publication of this research paper.

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