Optimization of Mechanical Properties of Woven Bamboo and Jute Fiber Reinforced in Epoxy Composites Using Taguchi Methodology

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Abstract

Low-density yet robust, rigid, and high-impact strength structural materials are required for aerospace, transportation, marine, and space applications. Materials called composites can meet the demands of modern technology. The potential of woven Bamboo and jute fiber to improve the mechanical characteristics of Epoxy Matrix has not been explored. The investigation focuses on the Taguchi technique for optimizing parameters affecting the mechanical characteristics (tensile and flexural) of woven hybrid Bamboo and jute fiber reinforced in epoxy composites. The factors include % of Bamboo, % of Jute, and % matrix materials. The Taguchi technique was employed to design the experiments, and the outcomes were analyzed. The experimental data obtained were statistically analyzed, and optimized values of various parameters were depicted. The results showed that 30% reinforcement, i.e., 10% Bamboo and 20 % jute, and 70% matrix material, show the highest mechanical properties. They have shown to be more advantageous as reinforcements in composite materials used in the polymer industry and may be used to make boards for skating, safety helmets, electric-powered switchboards, vehicle dashboards, and parcel shelves, among many other applications.

Keywords: *Bamboo, Jute, DOE, Taguchi, Tensile, Flexural, Optimization*

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1. INTRODUCTION

Natural fibers are agricultural plants growing in many places of the world. They are extensively employed in manufacturing ropes, textiles, carpets, and bags. Natural fiber consists primarily of cellulose in an amorphous lignin and hemicellulose matrix. Natural fiber has a cellulose concentration ranging from 60 to 80wt.%, making it one of the most essential components of natural fiber. The hemicellulose concentration ranges from 5-20%. The moisture content of fibers might reach 20%. Natural fiber composites, inner panels, seat backs, and inner roof panels are utilized in the automobile sector[1]. The fiber's surface is hydrophilic, making it unsuitable for use with hydrophobic polymers[2]. Natural fibers have an edge over synthetic fibers regarding cost and processing methods. On the other hand, natural fibers have poorer mechanical qualities than synthetic fibers. Another drawback of natural fiber composites is their inability to absorb moisture[3]. Plastic-based composites are notable for their low weight, strength, chemical resistance, and stability. They are used in medium-range sports, electronics, and aviation applications.[4] However, environmental issues, including waste disposal and non-biodegradability, are these materials' primary drawbacks[5]. As a result, numerous researchers have been encouraged to develop biodegradable, environmentally friendly composites[6]. These fibers were originally used between the years 1920 and 1930. It is utilized in aeronautical applications to minimize component weight [7][8]. A product's life cycle might end with either combustion or composting[9].

Among the various techniques like genetic algorithms and artificial neural networks, the Taguchi method is used in the present study for the optimization process. In the Taguchi technique, fewer tests are required, and it can extract information more precisely and efficiently than other approaches. DOE is a robust statistical tool for enhancing product/process designs and solving production challenges. According to Dr. Genichi Taguchi, a standardized version of the DOE allows one to quickly understand and use the approach of product design optimization and production problem research. Since its introduction in the United States in the early 1980s, engineering and scientific specialists have frequently used the DOE Taguchi approach to enhance products and processes. Experiments of many types are possible in modern industrial contexts. Some have few components, some have many, and others require a mix of factors.

However, most studies fall into the group where all aspects have the same levels. The Taguchi approach uses a predetermined number of orthogonal arrays to handle several common experimental conditions. Variables directly impact the performance of the product or process under consideration. There are two kinds of factors: discrete (assumes known values) and continuous (can consider any workable value). Levels are the values or descriptions that characterize the state of the factor when the experiments are being carried out. To investigate the effect of an element, one must conduct experiments with two or more levels of the factor. Two levels are the minimum needed for comparing performance and determining influence. When examining a factor at two levels, you must assume that the factor's effect on the outcome is linear. Evaluating three or four levels of an element can reveal if the factor has a non-linear response[10].

Most research on natural fiber composites has concentrated on experimental studies of the mechanical characteristics of natural composites. The relationship between mechanical characteristics and distinguishing factors such as composite components and operating conditions is critical for creating appropriate composites to meet diverse functional needs. The optimization of characteristic parameters is essential. In the current investigation, Bamboo and Jute fiber is being explored for composite preparation. They have better bonding qualities, which results in good mechanical properties. The experimental data of tensile and flexural strength and modulus were optimized using the Taguchi method.

2. *Materials and Methods*

2.1. Bamboo:

An environmentally friendly natural material is bamboo fiber. Compared to other natural fibers, it develops more quickly. The atmosphere's carbon dioxide is eliminated. It is a member of the Bambusae family[11]. Bamboo fiber has the key features of being tall and perennial and varies in height from 10 cm to 40m. Around 70 genera of bamboo plants are produced worldwide in various environmental situations. They have almost 1000 species[12]. As shown in figure 1.1, bamboo plant fiber has higher mechanical strength and stiffness than other plant fibers. It also has a low density at a lower cost.

Bamboo fiber is brittle compared to other natural fibers. As shown in figure 1.2, multiple techniques are utilized to recover raw bamboo fibers. Chemical extraction, mechanical extraction, and steam explosion extraction are examples of extraction procedures[13]. Figure 1.3 shows the woven form of the bamboo fabric. China is called the "Kingdom of Bamboo" since more than 400 different types of Bamboo are grown[14]. In 2010, Chinese bamboo plantations reached 5.38 million hectares, increasing by 100,000 hectares per year.

Fig.1.1 Bamboo tree

Fig.1.2 Extracted fiber

Fig.1.3 Woven fiber

2.2. Jute:

Jute fibers (JF), a popular stem-type herbal fiber, are indigenous to India, Bangladesh, and Nepal. Jute was previously only used for ropes, twines, sacks, and hessian textiles. Bast fibers are currently employed in the automobile industry for seat backs, inside door panels, trunk liners, and so on [15][16]. A jute plant with a base stem diameter of 25 mm and a potential height of 2.5 m is shown in Figure 1.4. A natural fabric that may be spun into solid threads, jute is soft and long. The largest producer of JFs is India (1,968,000 tons), followed by Bangladesh (1,349,000 tons) and China (29,628 tons)[17]. Figure 1.5 depicts the extracted raw jute fiber, whereas Figure 1.6 depicts the weaved fiber.

Fig.1.4 Jute plant

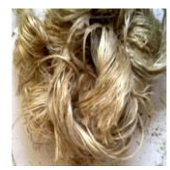


Fig.1.5 Raw jute fiber

Fig.1.6 Woven Jute fiber

Table 1 shows the chemical compositions of different natural fibers.

Table .1 Chemical compositions of a few natural fibers

Natural Fibers	Hemicellulose %	Cellulose %	Lignin %
Coir	0.14-0.25	32-43	40-46
Jute	13-24	61-72	12-16
Bamboo	12.46	60-73.83	10.15
Areca	12	-	13.2-24
Maize silk	20-23	37-42	10-14
Banana	19	62.60	5
Sisal	12	65-72	10-15

2.3. Epoxy Matrix:

These thermoset materials are employed in composites and structural applications. The following are the characteristics of epoxy resin. The present investigation uses Lapox L12 and K6 hardener[18].

1. It offers sufficient electrical insulation.
2. Epoxy resin functions better at high temperatures than thermoplastics.
3. It possesses good dimensional accuracy because of the limited shrinkage it undergoes while cooling.

4. It has excellent adhesion to surfaces.
5. It has outstanding physical qualities including flexibility, toughness, and abrasion resistance.
6. It is chemically inert.
7. It is Low cost and easy of manufacture.

Table.2 Material Properties

Property	Epoxy[19]	Bamboo [20]	Jute [21]
Density (kg/m3)	1.2	1.4	1.45
Tensile strength (MPa)	70- 80	400-800	393-773
Poissons ratio	0.35	0.3	0.35
Young's Modulus (GPa)	3.45	21	20
Poisons Ratio	0.35	0.3	0.38
Rigidity Modulus (GPa)	1.277	0.582	7.24

2.4. Rule of Mixture:

The equation depicts the analytical equation used to construct composites with various matrix and fiber volume fractions combinations. [22].

Vc = Vf + Vm ----------Eqn (1)

Vf = Volume fraction of Fiber Component

Vm = Volume of Matrix

Vc = Volume of Composite

3. FABRICATION PROCESS AND METHODOLOGY

3.1. Fabrication of Mold:

A mild steel metallic mold measuring 300mm x 300mm x3.2 mm is constructed to produce the required specimens.

3.2 Hand Layup Method:

The production of this open molding technology requires minimal tooling and is simple[23]. This method is employed for laying reinforcements and matrix with varied orientations, such as 0^0 and 90^0.

3.3 Tensile Test:

Tensile test specimens were prepared to the required dimensions as per ASTM D3039[24]. The test is carried out with a Computerized UTM with a capacity of 100kN. The specimen is securely secured in a tensile fixture, and a 5mm/min load is applied at a room temperature of 25 ^{0}C. Tensile characteristics were investigated after readings were taken.

3.4 Flexural Test:

Test samples are prepared to the required dimensions as per ASTM D790[25]. This test is done by fixing the specimens in a fixture using a three-point bending condition. The experimental setup used for this is a computerized UTM 100kN capacity. The crosshead speed for the test was kept at 2mm/min.

3.5 Experimental Design:

The L9 orthogonal array is chosen using the Taguchi technique. 9 experimental runs are generated using the Taguchi L9 orthogonal array design. Table 3 depicts the control variable and its various levels. The experimental observations are further transformed into signal/noise (S/N) ratio using MINITAB 20.4 software.

The Taguchi technique applies the loss function to determine the difference between the experimental findings and the required data. The loss function calculates the signal/noise (S/N) ratio. The S/N ratio has three quality characteristics: larger-is-better, smaller-is-better, and nominally-is-better. Table 4 indicates the composition details used for that particular sample[26].

Table. 3 DOE control factors and Levels

Control Factors	Levels		
	1	2	3
%Matrix	70	60	50
% Bamboo	40%	50%	60%
% Jute	60%	50%	40%

4. Results and Discussions:

4.1. Tensile and Flexural Test Results:

A series of tensile and flexural tests are conducted for the volume fractions in Table 5. The matrix material varies from 70 %, 60%, and 50%, as shown in the table. Similarly, the reinforcements like %jute and % bamboo differ from 30%, 40%, and 50%. In that reinforcement, i.e., for 30% reinforcement, three levels are considered, they are 40% bamboo and 60% jute, 50% bamboo and 50% jute, and 60% jute and 40% bamboo in the composite material, respectively. The results or responses of the tensile and flexural tests like tensile strength and tensile modulus, flexural strength, and flexural modulus are tabulated in Table 5.

4.2. Optimization of Tensile Test Results:

Figures 1.7 and 1.8 show the mean effects plot for tensile strength and modulus. The study included three control variables: the proportion of epoxy and the fraction of Bamboo and Jute as reinforcements. The main effect plot provides the optimal elements and conditions for achieving the best tensile strength and modulus. The ideal composite, represented by the mean effect plot, implies that the sample S1, i.e., fiber with 30% reinforcement, i.e., 40% Bamboo and 60% Jute, provides the most desirable results. And a matrix with 70% would get the best results.

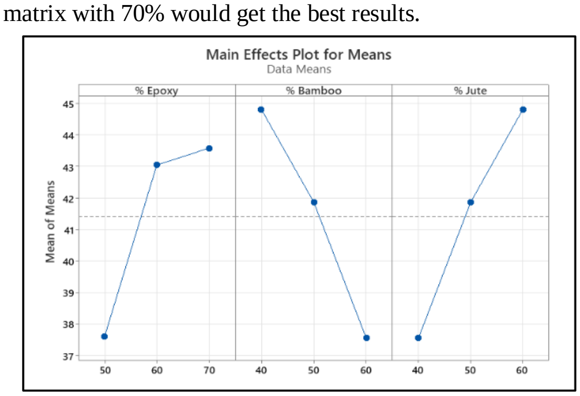
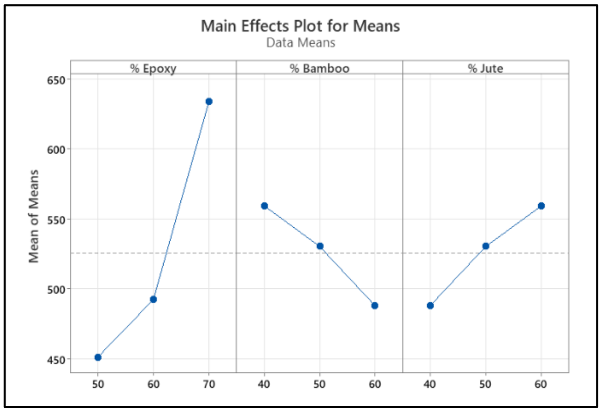


Fig. 1.7 Mean of means ratio graph for tensile strength.



4.3 Optimization of Flexural Test Results:

Similarly, flexural strength and modulus mean of means plots are shown in figure 1.9 and 1.10. The main effect plot for flexural strength and modulus of hybrid fiber epoxy composites suggested that the 30% reinforcement, i.e., bamboo fiber 40% and Jute fiber 60%, are the better combinations, and 70% resin would give the optimum result.

Fig. 1.8 Mean of means ratio graph for the tensile modulus.

Table.4 Content details for the composition of composites

Sample. No.	% Matrix	% Reinforcement						
		Total %	Bamboo%	Jute%	Actual % of Bamboo	Actual % Jute	Number of Bamboo Layers	Number of Jute Layers
1	70	30%	40%	60%	10	20	3	4
2	70		50%	50%	15	15	4	3
3	70		60%	40%	20	10	6	2
4	60	40%	40%	60%	15	25	5	3
5	60		50%	50%	20	20	6	4
6	60		60%	40%	25	15	7	5
7	50	50%	40%	60%	20	30	6	5
8	50		50%	50%	25	25	7	4
9	50		60%	40%	30	20	8	3

Table 5 Experimental results of the mechanical properties of hybrid composites.

Sample No.	Tensile Strength MPa	Tensile Modulus MPa	Flexural Strength MPa	Flexural Modulus GPa
1	47.411	695.4	80.25	9.06
2	44.68	650	76.25	8.75
3	38.63	556	64	8.36
4	46.254	556.314	64.382	7.8
5	44.318	466.286	61.562	7.76
6	38.546	454.276	59.645	7.662
7	40.75	425.541	56.254	8.043
8	36.58	474.293	55.263	7.485
9	35.48	453.55	54.36	7.426

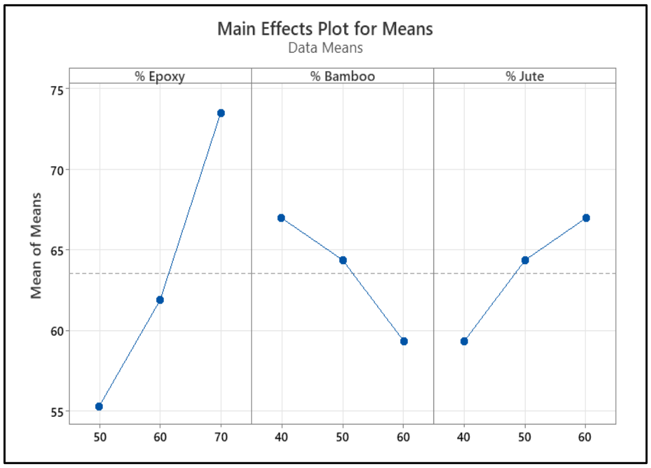


Fig. 1.9 Mean of means ratio graph for Flexural strength.

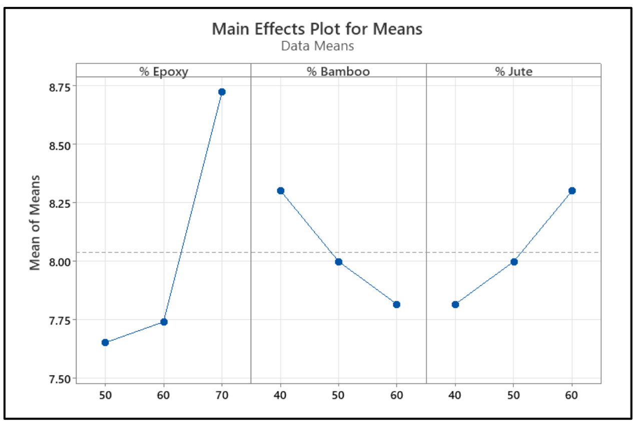


Fig. 1.10 Mean of means ratio graph for Flexural modulus (GPa)

3.2 Probability Plot:

As illustrated in figure 1.11, the probability plot is a graphical tool for determining if a data set follows a certain distribution, such as the normal or Weibull distribution. The normal probability plot is generated by displaying the sorted data versus predicting the means or medians of the appropriate order statistics. The points should be near a straight line if the findings align with a sample from a normal distribution. A straight line can be fitted to the points as an indication. The larger the deviation from normality, the more the points diverge from this straight line. A normal 95% CI indicates that 95% confidence interval, and it can say that there is only a 5% chance of deviation.

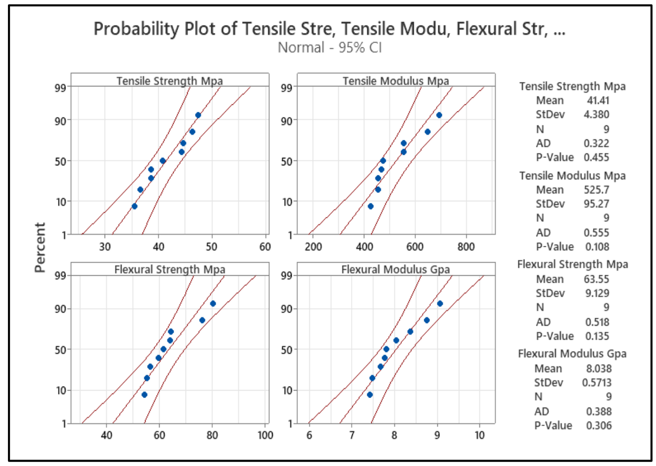


Fig. 1.11 Probability plot of tensile strength and modulus, flexural strength and modulus

5. CONCLUSIONS:

Taguchi method has been used to design the experiment and optimize tensile, flexural strength, and modulus of woven Bamboo and juber epoxy composites. The method was successfully used to improve the mechanical properties of composite materials. The results showed that the S1 sample has a maximum modulus of elasticity of 695.44Mpa. The highest flexural modulus was found to be 9.065GPa in S1 laminate. The 30% reinforcement, i.e., 10% Bamboo and 20% Jute, and 70% resin composition, gives the highest mechanical properties.

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