Multi-objective Optimization of Carbon/Glass Hybrid Composites with Newly Developed Resin (NDR) using Grey Relational Analysis.

Abstract:

Purpose:

The focus of this research work is on the effect of design variables such as the carbon layer in stacking sequence, the use of different resins on the bonding strength of fibers, stacking angle of fibers and thickness of laminates on the mechanical properties of carbon/glass fiber hybrid composites. The mechanical properties are Tensile, Shear and 3-point Flexural strength. Carbon and Glass fibers have enchanting properties and excellent weight to strength ratio in comparison with the metals.

Methodology:

To determine the most significant design variable for optimum mechanical properties of the hybrid composite, the Taguchi Technique has been used. For this purpose, the L_{16} orthogonal array has been formed. The Signal to Noise (S/N) ratio plots was obtained to determine the effect of design variables on mechanical properties such as Tensile, Shear and 3-point Flexural strength. The statistical analysis was carried out by using the Analysis of Variance (ANOVA).

Findings

Through this analysis, it was observed that different resins and stacking angles were the most significant factors for tensile, shear and flexural strength of hybrid composites. The contribution of resin and stacking angle was respectively 55.22% and 30.21% on tensile strength, 43.32% and 53.27% on shear strength and 75.55% and 20.67% on flexural strength at 95% confidence level. A multi-objective optimization was carried out using Grey Relational Analysis (GRA) to identify an optimum combination of design variables. The GRA shows that the optimal design variable setting for maximum tensile, shear and flexural strength is as A2B2C4D1. (i.e. Stacking sequence G/C/G/G, stacking angle is 45^0, the type of resin is NDR and laminate thickness is 0.2cm). It is seen that the effect of the type of resin used is significant in the bonding strength of fibers.

Originality

Three conventional types of resins along with the newly developed resin (NDR) were studied for their effect on the tensile, shear and flexural strength of hybrid composites. The validation test was carried out at a selected set of optimum design variables A2B2C4D1. The test indicates an improvement in grey relational grade by 1.366% showing the tenacity of grey relational analysis. Also the NDR enhanced the mechanical properties for commercial applications like beam, tank wall etc.

Keywords: NDR; GRA; ANOVA; Hybrid; Carbon fiber; Glass fiber

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1. Introduction:

Composite materials are recognized for high specific modulus, high specific strength, high resistance to corrosion, low weight. They can be used in a wide range of applications like aerospace, automotive, marine, defense, drilling, biomedical, etc., giving them an advantage over traditional materials such as metals and ceramics. [1-11].The mechanical properties of composite material are affected by the nature of fibers, type of resin, stacking angle, stacking sequence, and fiber volume percentage. Morye et al. [12] have shown that the aramid fibers with phenol-formaldehyde and polyvinyl butyral (PVB) resins have greater tensile strength and modulus than nylon 66. Wong et al. [2] highlighted that E-glass fibers along with epoxy matrix have better mechanical properties than phenolic resin. Therefore, the mechanical properties of composite laminates depend on these design variables. Dong et al. [13-19] have analyzed the tensile and flexural properties of carbon/glass epoxy hybrid composite using experimental and FEA approach and have observed the positive effect of substituting the partial carbon fiber with glass fibers. Other researchers [20, 21] have studied the effect of epoxy and polyester resin on the tensile strength of the natural fiber. The effect of both the resins on the tensile strength of eucalyptus fiber has been investigated. They have also investigated the effect of epoxy resin with glass and curaua fiber. Jesthi and Nayak [22] analyzed the effect of different stacking sequences of glass and carbon fiber on tensile, flexural and impact strength of laminates for marine applications. It is observed that tensile strength was increased by 14% and flexural strength by 43% in the hybrid composite compared with the plain Glass fiber reinforced polymer composites (GFRPC). Some researchers [23-25] also have analyzed the effect of stacking sequence of carbon, glass, and basalt fiber hybrid composite on mechanical properties through analytical, numerical and experimental analysis. It is seen that the stacking sequence has the positive effect of hybridization. Kalantari et al. [26, 27] have worked on multi-objective robust optimization of unidirectional glass/carbon fiber for flexural loading. The posteriori approach was used to optimize the cost and weight by considering the thickness and fiber volume fraction as design variables. Senthil Kumar et al. [28] used the Taguchi technique for the optimization of tribological properties of nano clay/epoxy/ glass fibers. Some researchers [29, 30] have adopted the GRA approach to optimize the process parameters of WEDM for metal composites. The most significant parameters affecting the WEDM process have been analyzed. Ghasemi et al. [31] have used the response surface method for the optimization of mechanical properties for polypropylene/talc/graphene composites. The effect of three variables i.e. polypropylene, graphene, and maleic anhydride grafted polypropylene on the mechanical properties of composites has been analyzed. The glass fibers are recognized for their lower cost and carbon fibers are identified for its high strength to weight ratio. Some researchers [35, 36] have investigated the mechanical demeanor of fiber metal laminate (FML). They have used the titanium, aluminum metal to form a hybrid composite structure with carbon and glass fiber bonded by epoxy resin. Xinwie et al. [37] observed that tensile strength and elastic modulus of Zn-Al alloy were improved by introducing the carbon fiber in the composite structure. Also, some researchers [38, 39] used the FEA approach to investigate the effect of stacking angle on the strength of the shaft.

From this brief literature review, it is seen that little amount of work on optimization of mechanical properties taking into consideration the combined effect of design variables such as stacking angle, stacking sequence, different resins, and thickness of composite laminates has been carried out. Also, a very little amount of work was carried out in the resin development. To determine the exact significance of these variables and to obtain the optimum combination the scientific approach must be used.

As such, the focus of this research work is on the optimization of the design variables like stacking angle, stacking sequence, different resins, and thickness of composite laminates which affect the mechanical properties of hybrid composites. For this purpose, the Taguchi technique and the method of Grey Relational Analysis (GRA) are used to identify the optimum combination of design variables. In this case, the effect of the above-mentioned design variables, particularly of the newly developed resin (NDR) on the mechanical properties of hybrid composites has been investigated.

From the existing literature, it is scrutinized that, the focus of current works of literature is to investigate the impact of single design variables on the mechanical properties of the composite. The real ongoing challenges in the industries are lack of statistics on the impact of various design variables on the strength of the composite laminate. This research supports to focus on the exact influence of variables on the mechanical strength of the composite laminate. Also, there is a lack of research to investigate the impact of resins on bonding strength. This research helps to investigate the effect of Newly Developed Resin on the strength of composite laminate compared with existing resins such as epoxy, polyester, and vinyl ester. After a brief investigation through the experimental results, it has been determined that the type of resin and stacking angle are the most significant factors on the Mechanical Properties of Composite laminate.

2. Design variables:

First of all, the necessary information for i) the mechanical properties of glass and carbon fibers selected for hybrid composite sample, ii) the types of resins selected to analyze the effect on mechanical properties and bonding strength of the fibers, and iii) stacking angle and stacking sequence are presented.

a) Fibers:

For reinforced composite laminate preparation two fibers were chosen, i.e. 200 GSM Carbon Fiber and 900 GSM Glass Fiber. Table 1 demonstrates the mechanical properties of these fibers.

Table 1. Mechanical properties of glass and carbon fiber

Sr.No.	Specifications	900 GSM glass fiber	200 GSM carbon fiber
1	Modulus of elasticity (MPa)	70000	235000
2	Tensile Strength (MPa)	3500	3850
3	Density (Kg/m^3)	2700	1650
4	% elongation	4.5	1.55

b) Resins:

Four different resins were selected to analyze the effect on the mechanical properties of reinforced composite and bonding strength of the fibers. Three resins are conventional resins i.e. epoxy, vinyl ester and polyester and the fourth one is the Newly Developed Resin (NDR) from polyethylene and polyurea group. The NDR has been developed in SP Concare Pvt.Ltd. Sangli. (Maharashtra, India). Polyurea can be produced by reacting to a component that constitutes a Diisocyanate with a component that constitutes polyamine. The synthesis of NDR is shown in

Fig. 1. The detailed formulation and contents to prepare a new resin are given in Table 2. The novelty of this research is the development of new resin called NDR and to investigate the effect of NDR on the bonding strength of the fiber.

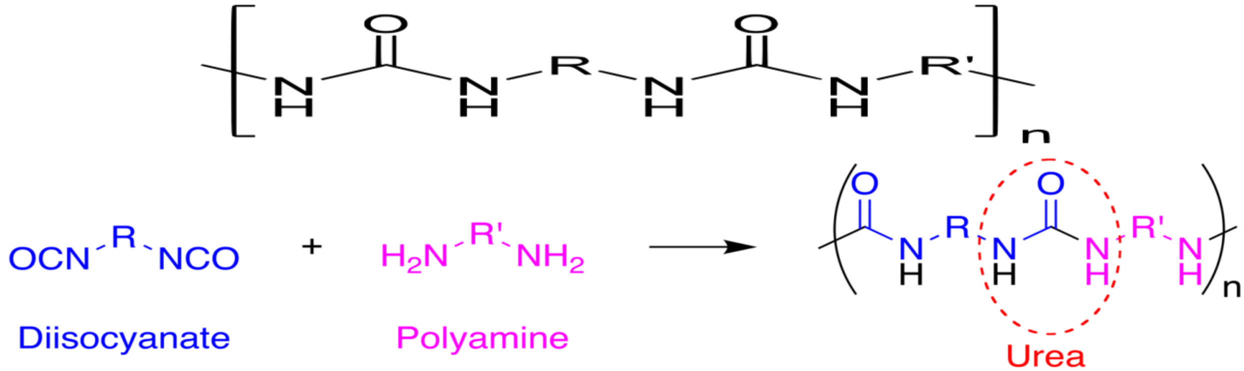


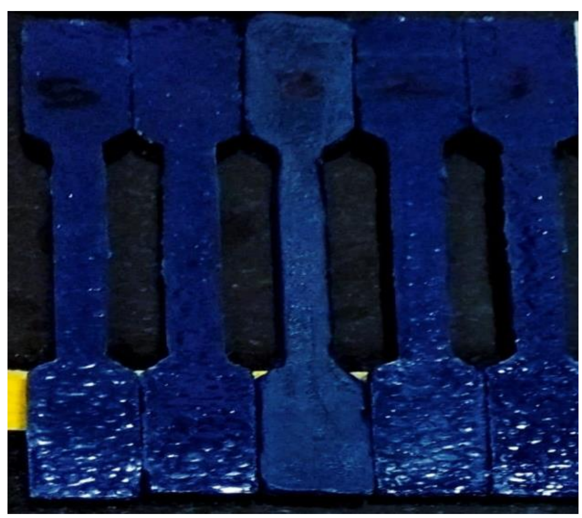
Fig.1 Synthesis of NDR

Table 2. Formulation and contents of NDR

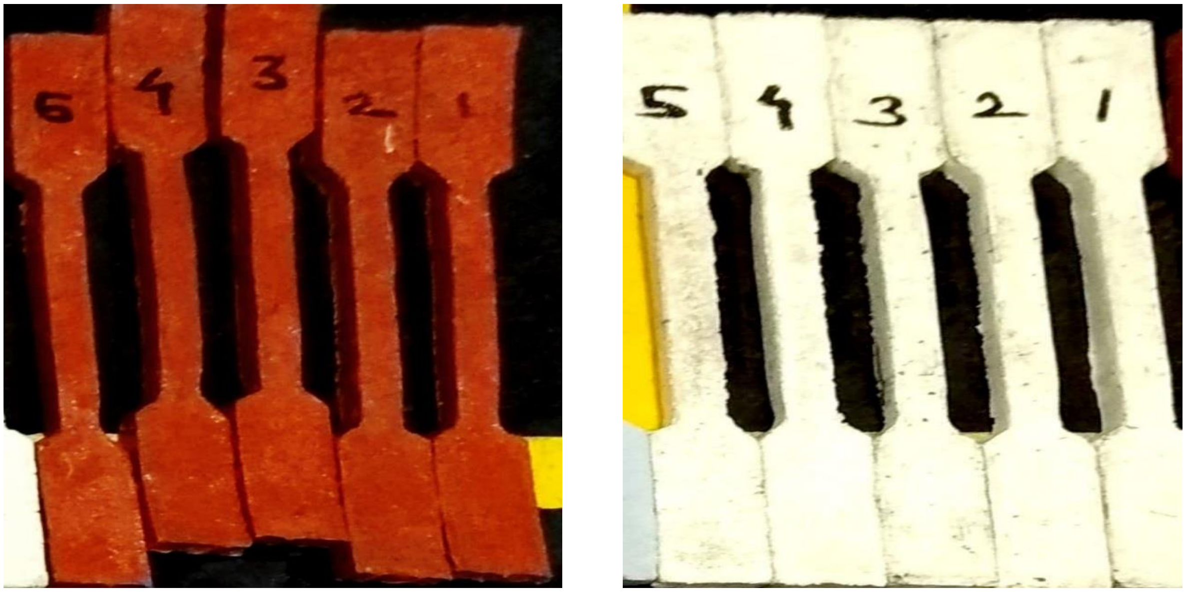
Sr. No.	Contents	Percentage
1	Polyol	47-52
2	Barytes	20-24
3	Moisture Sieves	5-7.5
4	Pigment	1.5-3.5
5	Silica Powder	0-1
6	Hardner	17-20

The tensile test was performed on resins according to ASTM D-412. The samples of resin are shown in Fig.2. These specimens were manufactured in the rubber mold. To determine the mechanical properties of resin five specimens for each resin were manufactured as per the ASTM D-412 standards. Fig. 2(a) shows the specimens of epoxy resin. Similarly, Fig 2(b), (c) and (d) indicate the specimens of vinyl ester, polyester, and NDR resins respectively.

(a)Epoxy resin specimens



(b) Vinyl ester resin specimens



(c) Polyester resin specimens (d) NDR specimens

Fig.2 (a) Epoxy resin (b) Vinyl ester resin (c) Polyester resin (d) NDR

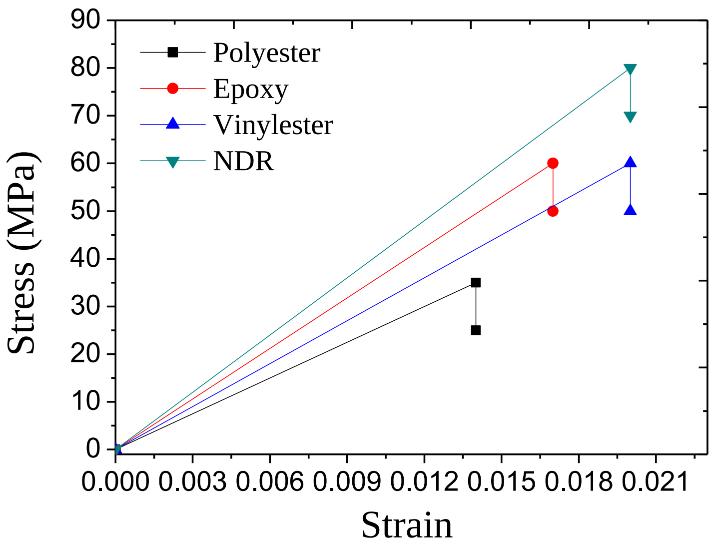


Fig.3 Comparative Graph of Stress vs. Strain for resins

The comparative results of stress vs. strain are illustrated in Fig.3. The NDR gives the highest strength compared to the other resins. The detail values of stress and strain are presented in Table 3. The cost of all resins indicates that NDR is cheaper for the industry and gives more strength compared with the other resin. The detailed properties for NDR after the investigation are represented in Table 4.

Table 3 Tensile Stress and Strain values for different resins

Resin	**Stress (MPa)**	**Strain**	Cost in INR
Epoxy	60	0.017	500/Kg
Polyester	35	0.014	350/Kg
Vinyl ester	60	0.02	350/Kg
NDR	80	0.02	270/Kg

Table 4 Physical properties of NDR

Tensile Strength (MPa)	Flexural Strength (MPa)	Modulus of Elasticity (MPa)	Density (Kg/Litre)	Viscosity (cps)
80	**40**	**3500**	**1.25**	**2700**

c) Stacking Angle:
Four stacking angles 0^0, 45^0, 90^0 and 135^0 of carbon and glass fibers were selected to analyze the effect on mechanical properties.
d) Stacking Sequence:
In this research work, hybrid composite i.e. Glass and Carbon fibers were considered to investigate the effect of the carbon layer in the stacking sequence. As per ASTM standards, the thickness of the laminate must be maintained in certain laminate. So, to manufacture the laminate as per the ASTM standards the four layers are selected. Carbon fibers are costly than glass fibers. Hence, one layer has been manufactured with a carbon layer and three layers have been manufactured by glass fiber. The glass fiber is having a higher tensile strength compared with metal like steel. So, based on the fiber cost to strength ratio for the investigation the three layers of glass were incorporated. To investigate the exact effect carbon fiber on the strength of the laminate structure its sequence has been varied from the bottom layer to the top layer. The desire application for the manufactured laminated is useful to set the basic properties for the composite structure like a shaft, beams, etc.

3. Design of Experiments using Taguchi Method

In composite materials, the performance and reliability of any component depend upon the properties of the laminate. The design variables like stacking sequence, stacking angle, the bonding strength of resin and thickness strongly affect the properties of the composite laminates. To determine the exact effect of these design variables on the mechanical properties of laminate, the engineering approach is to decide the optimum combination of design variables. Taguchi method can be applied for the optimization of design variables to obtain optimum combination with the lower cost and a minimum number of experiments. The Taguchi method stands on the technique of matrix experiments, known as orthogonal array (OA). The OA was selected to achieve the optimum level of each design variable. According to the Taguchi method, the objective functions are classified into three categories, namely, “smaller the better type”, “larger the better type” and “nominal the best type”. The mechanical properties such as Tensile strength, Shear strength, and Flexural strength are to be maximized and hence ‘larger the better type’ objective function has been selected in the present study. The selected design variables and their recognized levels as per L_{16} OA are presented in Tables 5 and 6 respectively.

Table 5.Design variables and their levels

Parameter	**Code**	**Level 1**	**Level 2**	**Level 3**	**Level 4**
Stacking Sequence(A)	StSq	C/G/G/G	G/C/G/G	G/G/C/G	GGGC
Stacking Angle (^{0}) (B)	StAn	0	45	90	135
Resin(C)	Re	Epoxy	Polyester	Vinyl ester	NDR
Thickness (cm)(D)	Th	0.2	0.3		

Table 6.Design of Experiments using L_{16} orthogonal array

Experiment Number	Levels of Design variables			
	StSq	**StAn(^{0})**	**Re**	**Th(cm)**
1	C/G//GG	0	Epoxy	0.2
2	G/C/G/G	45	Epoxy	0.2
3	G/G/C/G	90	Epoxy	0.3
4	G/G/G/C	135	Epoxy	0.3
5	G/C/G/G	0	Polyester	0.3
6	C/G/G/G	45	Polyester	0.3
7	G/G/G/C	90	Polyester	0.2
8	G/G/C/G	135	Polyester	0.2
9	G/G/C/G	0	Vinyl ester	0.2
10	G/G/G/C	45	Vinyl ester	0.2
11	C/G/G/G	90	Vinyl ester	0.3
12	G/C/G/G	135	Vinyl ester	0.3
13	G/G/G/C	0	NDR	0.3
14	G/G/C/G	45	NDR	0.3
15	G/C/G/G	90	NDR	0.2
16	C/G/G/G	135	NDR	0.2

4. Materials and Methods:

4.1 Fiber and Resins:

The glass fibers and carbon fibers, the binding resins (epoxy, vinyl ester, and polyester) were purchased from SP Concare Pvt. Ltd. Sangli (Maharashtra India). These ingredients are used in aeronautical applications [32] and hence selected for this research work.

The special resin developed by SP Concare Pvt. Ltd. Sangli (Maharashtra India), known as NDR, is taken for the comparative analysis.

4.2 Preparation of hybrid composite

The hybrid composite laminates were prepared by hand layup method. The fibers were overlapped layer by layer and saturated with the resins in open mold and curing was done at ambient temperature. The air bubbles were removed by using a vacuum pump. The components were manufactured according to OA.

4.3 Testing for Mechanical Properties:

4.3.1 Tensile Test:

The tensile test was carried out on hybrid composite specimens of size 250x25 mm according to ASTM standard D3039. The universal testing machine (UTM) of capacity 1000 KN with a crosshead speed of 2 mm/min was used for testing the specimens. The tensile specimens and experimental setup are shown in Figures (4) and (5) respectively. These specimens were manufactured by hand layup method. The specimens were manufactured according to the L_{16} orthogonal array. The three design variables are having four levels and one design variable is having the two levels. Hence, to reduce the number of experimental trials and cost of experimentation the L16 orthogonal array according to Taguchi Approach was incorporated in this investigation. The UTM machine of Mechasoft, India was used to carry out the tensile test.

Fig.4 Sample of Tensile Test specimens.

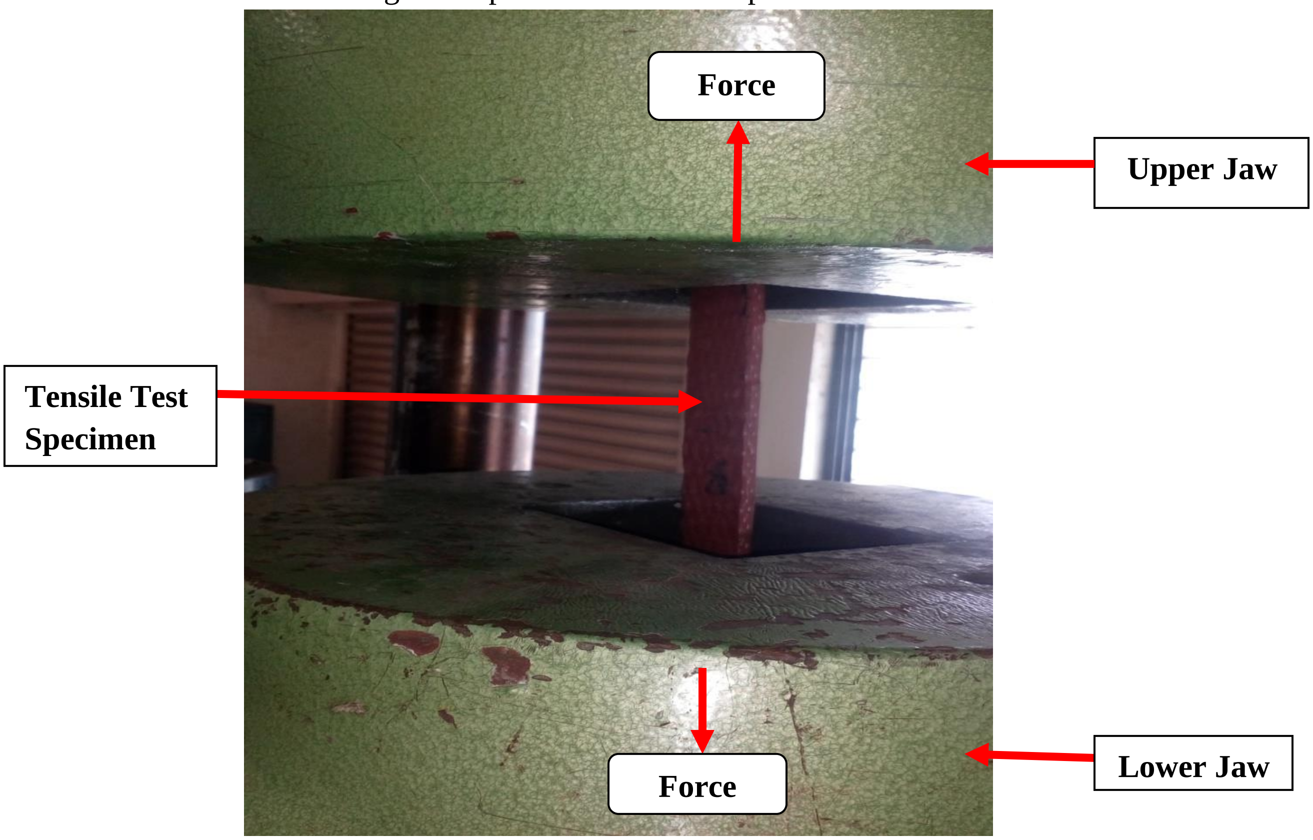


Fig.5 Experimental Setup for Tensile Test (UTM)

4.3.2 Shear Test:

The shear test was carried out on hybrid composite specimens of size 76x20mm according to ASTM standard D5379. The shear testing machine with a capacity of 100KN was used for testing. The shear test specimens and testing setup are shown in Fig. 6 and Fig.7 respectively. The shear test specimens were manufactured by hand layup method. The shear testing machine (Fig.7) of the Star testing system, India was used to conduct the experiments.

Fig. 6 Sample of Shear Test specimens

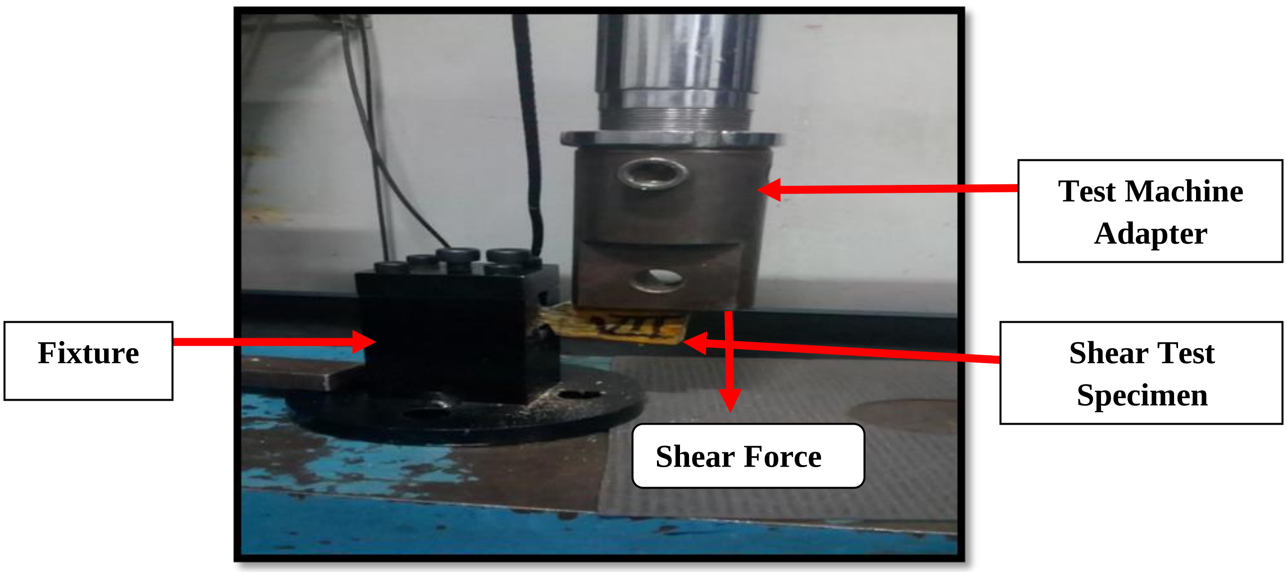


Fig.7 Experimental Setup for Shear Test

4.3.3 3-Point Flexural Test:

The size of the specimen for the flexural test was decided according to ASTM standard D790. The widths of the specimens were 12.7 mm and the span length was 16 times of thickness. The specimens were tested using a Universal testing machine (UTM) with a 50KN load cell. The sample specimens and testing setup are as shown in Fig.8 and Fig.9 respectively. The flexural test specimens (Fig.8) were also manufactured according to the hand layup method.

Fig.8 Sample of Flexural Test specimens

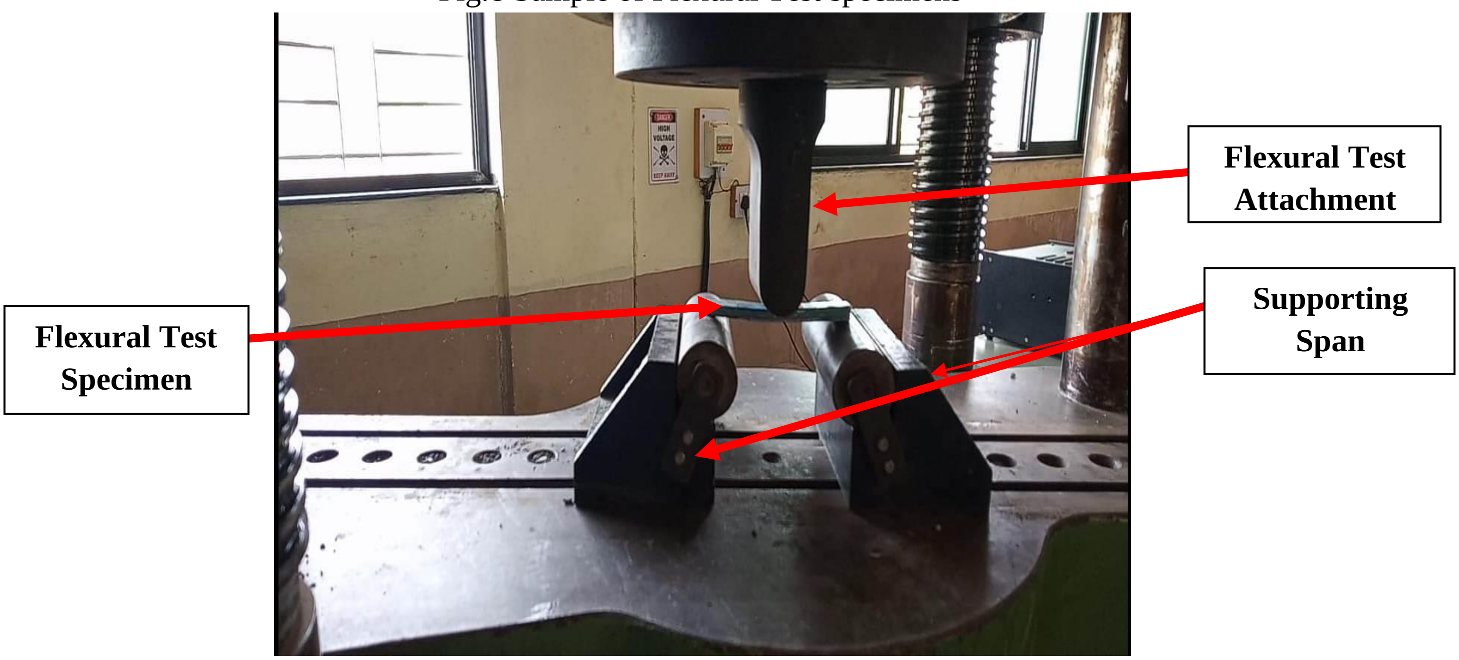


Fig.9 Experimental setup for 3-Point Flexural Test

5. Results and Discussions:

In all, sixteen experiments based on Taguchi L_{16} orthogonal array have been carried out (Refer Table- 6) and the results were obtained for Tensile strength (TS), Shear Strength (SS), and Flexural Strength (FS). The experimental results of mean and their associated S/N ratio values are presented in Table 7. The responses were analyzed by the ANOVA and Mean effect plot. The statistical software Minitab 16 was used to obtain these results of all experimental tests.

Table 7. S/N Ratios for TS, SS, and FS

Expt. No.	Average Tensile Strength (MPa)	S/N Ratio	Average Shear Strength (MPa)	S/N Ratio	Average Flexural Strength (MPa)	S/N Ratio
1	519.00	54.303	132.30	42.431	198.90	45.973
2	230.56	47.256	244.53	47.767	350.26	50.888
3	102.30	40.198	130.60	42.319	283.90	49.063
4	225.50	47.063	199.40	45.995	289.25	49.225
5	191.80	45.657	102.50	40.214	169.40	44.578
6	121.60	41.699	163.50	44.270	210.20	46.453
7	91.800	39.257	112.70	41.038	256.32	48.176
8	100.20	40.017	156.23	43.875	150.10	43.528
9	169.50	44.583	92.500	39.323	143.10	43.113
10	120.30	41.605	156.23	43.875	189.20	45.538
11	99.500	39.956	98.400	39.860	204.60	46.218
12	123.60	41.840	128.30	42.165	201.50	46.086
13	650.90	56.270	179.50	45.081	289.60	49.236
14	495.68	53.904	251.23	48.001	342.02	50.681
15	200.90	46.060	147.10	43.352	381.70	51.634
16	422.60	52.519	198.30	45.946	365.70	51.262

5.1 Main effect plot and Analysis of Variance (ANOVA):

The S/N ratios are used to measure responses of TS, SS, and FS to develop products and processes insensitive to the noise factor. Larger values of TS, SS, and FS indicate a good strength and higher mechanical properties of composite materials. As such, to calculate the S/N ratios, "larger the better type" objective function was used for TS, SS, and FS.

The S/N ratio for the "larger the better type" of the objective function can be computed by using Eq. (1) [30].

$$\boldsymbol{n = -10\, Log_{10}\left(\frac{1}{R}\sum_{j=1}^{R}(1/y_j^2)\right)} ------ \quad (1)$$

Where y_j is response value

At a 95% confidence level, all the results were obtained for the 16 experimental tests and it was statistically analyzed using ANOVA and the effects of the selected design variables were evaluated. P-value establishes whether the design variables are significant or not at a particular confidence level. For a 95 % confidence level, P-value must be less than 0.05 for the significant parameter. ANOVA identifies the effect of an individual variable on the mechanical properties of hybrid composites.

5.1.1 Analysis of Tensile Strength:

ANOVA Table 8 shows that the Stacking Angle and type of resin used are the most significant design variables. The percentage contributions of the stacking angle and the type of resins used are 30.21% and 55.23% respectively on the tensile strength of hybrid composite laminates and the rest of the design variables have a negligible effect on Tensile Strength. In Table 8, S is calculated in the response variable units and indicates how far from the fitted values the data values fall. The lower the S value, the better the answer is interpreted by the model. The higher the R-Sq value, the better the model fits the data. While the R-Sq value is 92.49% the statistical model will fit for the experimental data.

Table 8 ANOVA table for Tensile Strength

Source	DOF	Seq.SS	Adj.SS	Adj.MS	F Value	P Value	%C	
StSq	3	29530	29530	9843	1.53	0.316	6.88	
StAn	3	129642	129642	43214	6.70	0.033	30.21	Significant
Re	3	236981	236981	78994	12.25	0.01	55.23	Significant
Th	1	694	694	694	0.11	0.756	0.16	
Error	5	32237	32237	6447			7.51	
Total	15	429084						
S=80.2956	R-Sq=92.49%							

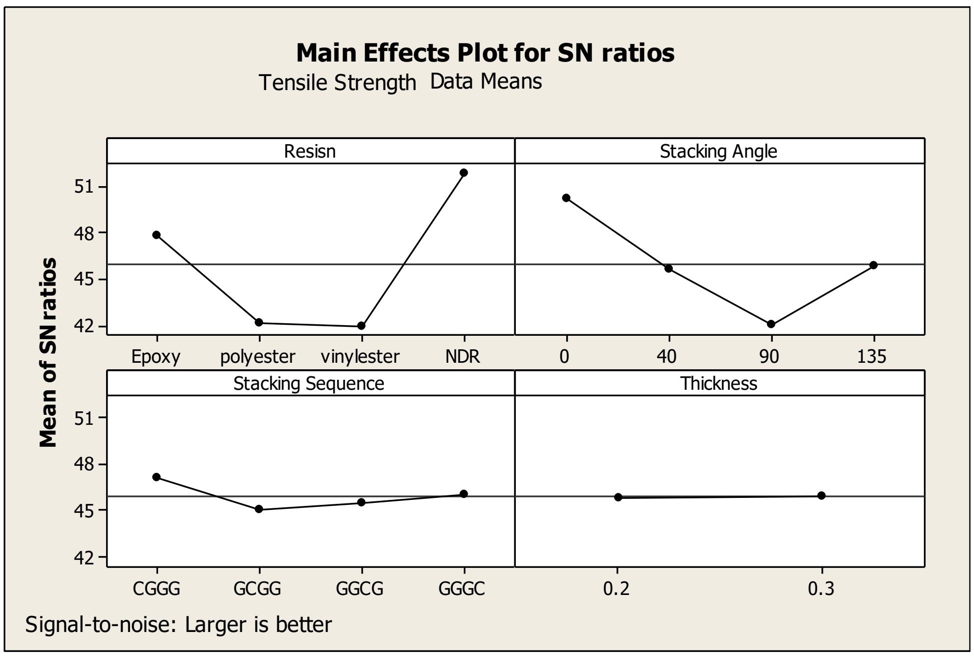


Fig.10 Effect of design variables on Tensile Strength (S/N data)

It is observed from the main effect plot for S/N ratio (Fig.10), that the effect of resin and stacking angle plays an important role in the tensile strength of hybrid composite laminates whereas the effect of stacking sequence and thickness is negligible. If the line is horizontal (parallel to the x-axis), then the main effect is not. Each factor level has the same effect on the response, and the mean of response is the same across all factor levels. If the line isn't horizontal then the main effect is there. Different levels of the factor affect the response differently. In fig.10, the lines for stacking sequence and laminate thickness are horizontal and hence there was no main effect of these design variables. For types of resins and stacking angles, the lines are not horizontal and hence these are the two most significant design variables.

5.1.2 Analysis of Shear Strength:

ANOVA Table 9 indicates that the Stacking Angle and type of resin used are the most significant design variables. The percentage contributions of the stacking angle and the type of resin used are 53.27% and 43.32% respectively on the shear strength of hybrid composite laminates and the rest of the design variables have a negligible effect on shear strength. It has been observed that in the case of tensile strength, the type of resin used is the most significant factor with 55.23% (refer table 8) whereas for shear strength the stacking angle is the most significant factor with 53.27%. In this ANOVA, S value is lower i.e.11.69 and the R-Sq value is higher i.e. 96.84%. Hence statistical model can better describe the response as well as it will be fit for the experimental data.

Table 9.ANOVA table for Shear Strength

Source	**DOF**	**Seq.SS**	**Adj.SS**	**Adj.MS**	**F Value**	**P Value**	**%C**	
StSq	3	46.3	46.3	15.4	0.11	0.949	0.21	
StAn	3	11531	11531	3843.7	28.09	0.001	53.27	Significant
Re	3	9376.7	9376.7	3125.6	22.84	0.002	43.32	Significant
Th	1	8	8	8	0.06	0.819	3.69	
Error	5	684.1	684.1	136.8			3.16	
Total	15	21646.1						
S=11.6969	R-Sq=96.84%							

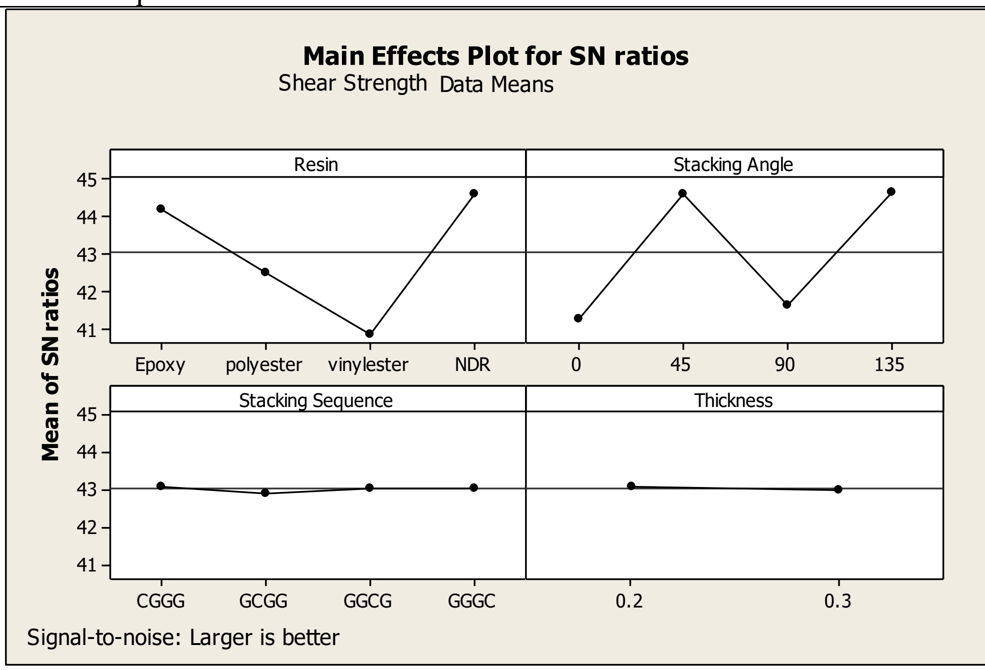


Fig.11 Effect of design variables on Shear Strength (S/N data)

Fig.11 shows the influence of the stacking angle is very vital on the shear strength of the hybrid composite laminates. As like tensile strength, the effect of stacking sequence and thickness is insignificant on shear strength. Epoxy and NDR gives approximately equal effect on shear strength.

5.1.3 Analysis of Flexural Strength:

ANOVA Table 10 revealed that on flexural strength the resin and stacking angle both are the significant parameters. It has been detected that the effect of resin is highly significant with a 75.55% contribution to the flexural strength of the hybrid composite laminate. Fig. 12 shows the effect of all design variables on flexural strength. NDR gives a higher flexural strength as compared with other resins. The influence of stacking sequence and thickness is not significant on the flexural strength of the hybrid composite laminate. In table 10, the S value is 13.49 which is lower and the R-Sq value is 98.62% which is very higher. Hence statistical model can better describe the response as well as it will be fit for the experimental data.

Table 10.ANOVA table for Flexural Strength

Source	DOF	Seq.SS	Adj.SS	Adj.MS	F Value	P Value	%C	
StSq	3	1589.2	1589.2	529.7	2.91	0.14	2.40	
StAn	3	13670.9	13670.9	4557.0	25.03	0.002	20.67	Significant
Re	3	49980.2	49980.2	16660.1	91.51	0.00	75.55	Significant
Th	1	1.4	1.4	1.4	0.01	0.933	0.0002	
Error	5	910.3	910.3	182.1			1.37	
Total	15	66152.1						
S=13.4927	R-Sq=98.62%							

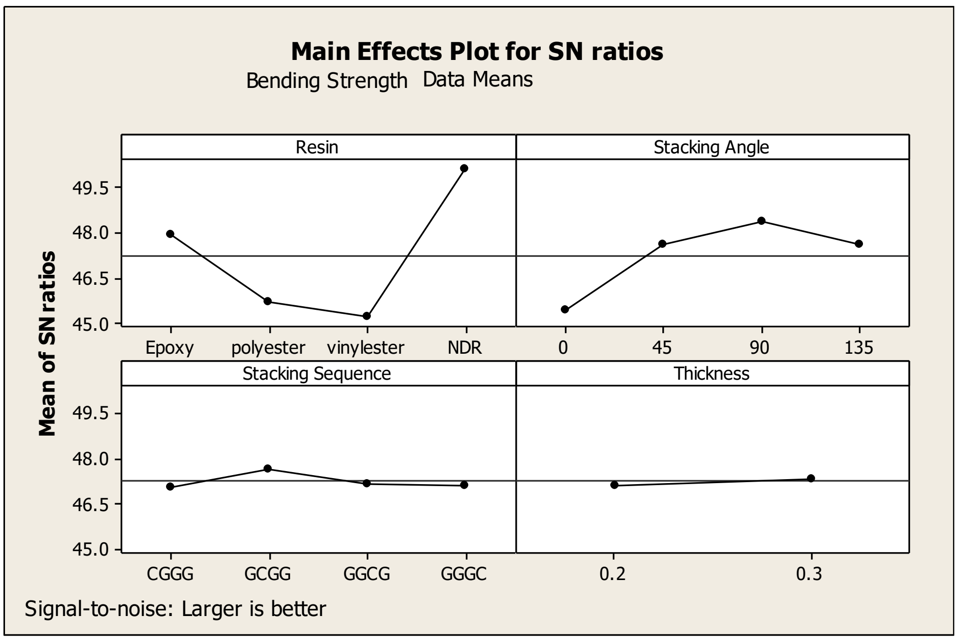


Fig.12 Effect of design variables on flexural strength(S/N data)

6. Multi-objective optimization using Grey Relation Analysis:

The mechanical properties of hybrid composite laminates are dependent on a number of parameters. Thus the task of multi-objective optimization of design variables is more intricate than the optimization of a single design variable. From earlier investigations, it is observed that the GRA method has the capacity to tackle the complexity in multi-objective optimization [30-31]. Some researchers [40, 41] have used both the GRA approach and the Firefly algorithm (FA) for optimization of process parameters for Laser Beam Cutting. They identified more improvement in optimization in combination with the Firefly algorithm than the GRA. Varun and Venkaiah [42] used the hybrid optimization method of FA with GRA to overcome the limitation of FA by providing the grey relational grading to the parameters. Some researcher shows GRA was the most effective method to carry out the optimization of multivariable over the other methods [33, 34]. As all algorithms have some limitations mentioned in the No Launch Theorem. [43] But GRA proves more tenacity in multi-objective optimization for non-homogeneous materials, and this technique has been the most effective method to tackle the nonlinear multiple dimensional problems. So, it has been decided to adopt the GRA approach to carry out the optimization of design variables. In this method, the multi-performance parameters have been converted into a single grey relational grade.

GRA has been carried out in the following step.

- Normalization of each performance parameter
- Obtaining the deviation sequence
- Determining the gray relational coefficient (GRC) and gray relational grade(GRG)
- Excerpting the optimal level variables and ANOVA of GRG
- Validation Test

Step I: Normalization of each performance parameter

The first step of GRA consists of normalization of the experimental data i.e. S/N ratio in order to convert the original sequence to a corresponding sequence (i.e. dimensionless data sequence). Measured values of response characteristics are normalized between zero to one. The TS, SS, and FS are the larger the better type characteristics. Hence, its original sequence can be normalized by using Eq. (2) and it has been shown in Table 11.

$$x_i^*(k) = \frac{x_i^0(k) - \min x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \qquad --- (2)$$

Where, $Xi^0(k)$ represents an original sequence, $Xi^*(k)$ represents comparability sequence,

i = 1,2,3,…m [m is the total no. experiment performed],

k =1,2,3,…n [n is the number of parameter considered], In present work m=16 and n=3.

Table 11.Normalized S/N ratio for TS, SS, and FS

Expt. No.	Tensile Strength (TS)	Shear Strength(SS)	Flexural Strength(FS)
Ref. sequence	1.0000	1.0000	1.0000
1	0.884	0.358	0.336
2	0.470	0.973	0.912
3	0.055	0.345	0.698
4	0.459	0.769	0.717
5	0.376	0.103	0.172
6	0.144	0.570	0.392
7	0.000	0.198	0.594
8	0.045	0.525	0.049
9	0.313	0.000	0.000
10	0.138	0.525	0.285
11	0.041	0.062	0.364
12	0.152	0.327	0.349
13	1.000	0.663	0.718
14	0.861	1.000	0.888
15	0.400	0.464	1.000
16	0.779	0.763	0.956

Step II: Obtaining Deviation sequence:

After normalization, it is essential to calculate deviation sequence $\boldsymbol{\Delta_{0i}k}$, which is the complete difference between the reference sequence x_0* (k) and the comparability sequence x_i*(k). The deviation sequence is presented in Table 12

$$\Delta_{oi}k = |x_0^*(k) - x_i^*(k)| \qquad --- (3)$$

Note: Reference sequence x_0* (k)=1

Table 12.Deviation Sequence for TS, SS, and FS

Deviation				**GRC and GRG**				
Deviation Sequence	**Δ_{01} TS**	**Δ_{01} SS**	**Δ_{01} FS**	**TS**	**SS**	**FS**	**Grade Value**	**Rank**
No.1, i=1	0.116	0.642	0.664	0.812	0.438	0.429	0.560	7
No.2, i=2	0.530	0.027	0.088	0.486	0.949	0.851	0.762	3
No.3, i=3	0.945	0.655	0.302	0.346	0.433	0.624	0.468	8
No.4, i=4	0.541	0.231	0.283	0.480	0.684	0.639	0.601	6
No.5, i=5	0.624	0.897	0.828	0.445	0.358	0.376	0.393	14
No.6, i=6	0.856	0.430	0.608	0.369	0.538	0.451	0.452	9
No.7, i=7	1.000	0.802	0.406	0.333	0.384	0.552	0.423	11
No.8, i=8	0.955	0.475	0.951	0.344	0.513	0.345	0.400	13
No.9, i=9	0.687	1.000	1.000	0.421	0.333	0.333	0.363	16
No.10, i=10	0.862	0.475	0.715	0.367	0.513	0.411	0.430	10
No.11, i=11	0.959	0.938	0.636	0.343	0.348	0.440	0.377	15
No.12, i=12	0.848	0.673	0.651	0.371	0.426	0.434	0.411	12
No.13, i=13	0.000	0.337	0.282	1.000	0.598	0.640	0.746	4
No.14, i=14	0.139	0.000	0.112	0.782	1.000	0.817	0.866	1
No.15, i=15	0.600	0.536	0.000	0.454	0.483	1.000	0.646	5
No.16, i=16	0.221	0.237	0.044	0.694	0.679	0.920	0.764	2

In above table 12, the ranks were given based on Grade values in ascending to descending order. According to OA, experimental trial no.14 gives less deviation as the grade value was higher than the other trials. Whereas, for trial no. 9 the grade value was lower as the deviation was higher.

Step III: Determining GRC and GRG:

Grey relational coefficient denotes the correlation between the best and actual experimental results. The GRC can be expressed by Eq. (4)

$$\gamma(x_0{}^*(k), x_i{}^*(k)) = \frac{\Delta_{min} + \zeta.\Delta_{max}}{\Delta_{0i}(k) + \zeta.\Delta_{max}} \qquad --- (4)$$

and, $0 < \gamma(x_0{}^*(k), x_i{}^*(k)) \leq 1$

Where,

Δ_{0i} (k) is the deviation sequence of the reference sequence x_0*(k) and comparability sequence xi*(k) (Refer Eq. 3).

And, $\boldsymbol{\Delta_{max} = max|x_0^*(k) - x_i^*(k)|} = 1$

$\boldsymbol{\Delta_{min} = min|x_0^*(k) - x_i^*(k)|} = 0$

$\boldsymbol{\zeta}$ = Distinguishing coefficient, $\boldsymbol{\zeta} \in (0, 1)$ for present study, $\boldsymbol{\zeta}$ was set as 0.5 based.

The GRG assist to detect the best set of design variables with which validation tests can be carried out. i.e. higher GRG exhibits the concerned parameter combination is very nearer to the optimum value. An average sum of GRG can be obtained from Eq. (5).

$$\boldsymbol{\gamma}(\boldsymbol{x_0}^*, \boldsymbol{x_i}^*) = \frac{\mathbf{1}}{\boldsymbol{m}}\sum_{\boldsymbol{i=1}}^{\boldsymbol{m}} \boldsymbol{\gamma}(\boldsymbol{x_0}^*(\boldsymbol{k}), \boldsymbol{x_i}^*(\boldsymbol{k})) \qquad --- \quad (\mathbf{5})$$

Where,

$\boldsymbol{\gamma}\ (\mathbf{x_0}^*, \mathbf{x_i}^*)$ is the GRG for m experiment, m = 1,2,3,..n

n = no. of performance characteristics = 3

Step IV: Excerpting the optimal level variables and ANOVA of GRG

Table 12 presents the grey relational grade for all comparability sequence, larger the grey relational grade, better the corresponding multi-objective characteristics, the value of GRG for experiment No. 14 is more which indicates that the design variables “Setting of experiment A3B2C4D2” offers best multiple design variables among the sixteen experiments.

The response table established from the Taguchi method for the S/N ratios of the grey relational grade is given in Table 13. The influence of each level of design variables on grey relational grade can be determined from the table. From the response table for GRG; the best set of combinations of the design variable is A2B2C4D1. The ranks have been decided from the maximum value of the design variable. The highest maximum value in Table 13 is 0.756 for the resin. Hence the resin is the most significant design variable and hence given rank 1. Similarly, table 13 indicates the lowest maximum value design variable is the laminate thickness and hence given the rank 4. From table 14, these sequence of these ranks has been justified from the percentage contribution of the design variables.

Table 13.Response table for the grey relational grade (GRG)

Level	**StSq**	**StAn**	**Re**	**Th**
1	0.517	0.515	0.597	0.543
2	0.574	0.628	0.417	0.539
3	0.511	0.478	0.395	-
4	0.563	0.544	0.756	-
Max	0.574	0.628	0.756	0.543
Min	0.511	0.478	0.395	0.539
Delta	0.063	0.149	0.360	0.004
Rank	3	2	1	4
The total mean value of GRG is 0.541				

6.1 ANOVA of GRG:

The calculated GRG was considered as a single response for the designed experiment and analysis of variance was carried out to determine the design variables which have the most significant effect on multi-objective response. ANOVA for GRG is presented in Table 14. From the table, it can be seen that resin is the most significant design variable for the optimum multi-response. All other design variables have a minor effect on the mechanical properties of hybrid composite laminates. In ANOVA of GRG, S value is very lower and the R-Sq value is extremely higher. Hence the statistical model can interpret the proper responses. Also, the model will perfectly fit with the experimental data.

Table 14.ANOVA for S/N ratios (GRG)

Source	DOF	Seq.SS	Adj.SS	Adj.MS	F	P	% C	
StSq	3	0.002032	0.002032	0.000677	0.14	0.932	0.4860	
StAn	3	0.04848	0.04848	0.01616	3.34	0.114	11.5969	
Re	3	0.34325	0.34325	0.11442	23.62	0.002	82.1093	Significant
Th	1	0.00007	0.00007	0.00007	0.01	0.908	0.0001	
Error	5	0.02422	0.02422	0.004844			5.8958	
Total	15	0.41804						
S=0.06960 R-Sq=94.2%								

The main effect plot for GRG is as shown in Fig. 13. The maximum GRG values were recognized at NDR resign, stacking angle 45^0, stacking sequence G/C/G/G and thickness 0.2 cm. Hence the combination of these design variables gives the optimal result for multi-response.

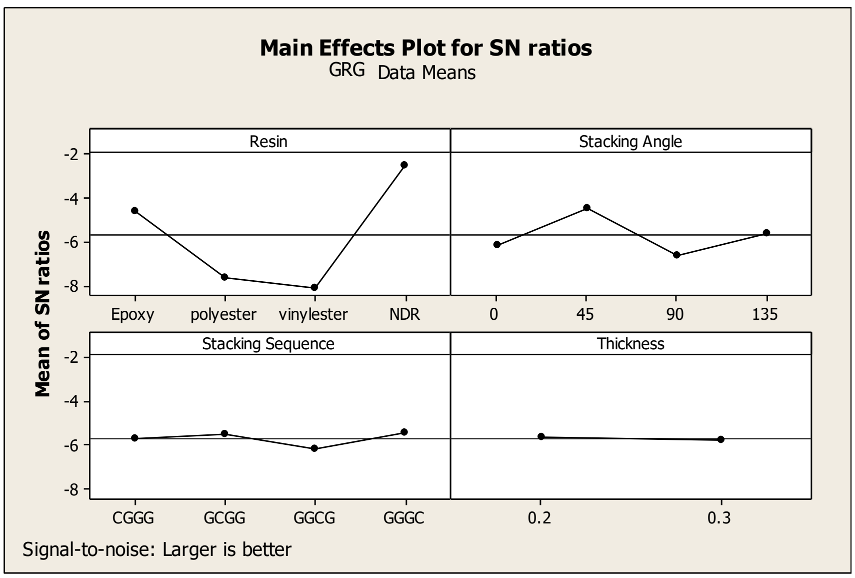


Fig.13 Main effect plot for GRG (S/N data)

<u>Step V: Validation (Confirmation) Test</u>

Subsequently evaluating the optimal parameters set, the next step was to determine the improvement of quality characteristics. The optimal Grey Relational grade $\boldsymbol{\eta_{opt}}$ is determined using Equation 6.

$$\boldsymbol{\eta_{opt}} = \overline{\mathbf{T}} + \left(\overline{\mathbf{A}}_{(1/2/\,3/4)} - \overline{\mathbf{T}}\right) + \left(\overline{\mathbf{B}}_{(1/2/\,3/4)} - \overline{\mathbf{T}}\right) + \left(\overline{\mathbf{C}}_{(1/2/\,3/4)} - \overline{\mathbf{T}}\right) + \left(\overline{\mathbf{D}}_{(1/2)} - \overline{\mathbf{T}}\right) \quad --(6)$$

Where,

$\overline{\mathbf{T}}$ = Total mean of the response

$\overline{\mathbf{A}}_{(1/2/\,3/4)}$, $\overline{\mathbf{B}}_{(1/2/\,3/4)}$, $\overline{\mathbf{C}}_{(1/2/\,3/4)}$, $\overline{\mathbf{D}}_{(1/2)}$ = Mean of GRG at an optimal level (i.e. maximum values of response at the first or second or third level of parameters A, B, C, and D respectively)

In the present work, $\overline{\mathbf{T}}$= 0.541

η_{opt} = 0.541+ (0.574-0.541) + (0.628-0.541) + (0.756-0.541) + (0.543-0.541)
η_{opt}= 0.878

Finally, a validation test was carried out using the optimum combination of the parameter (A2B2C4D1). Table 15 shows the comparison of predicted values of GRG with the initial setting as well as the experimental results of the optimal test parameter. The improvement in GRG from initial parameter combination A3B2C4D2 (G/G/C/G, 45^0, NDR, 0.3cm) to the optimal parameter combination A2B2C4D1 (G/C/G/G, 45^0, NDR, 0.2 cm) is 0.012, which is 1.366% of initial setting. This improvement was observed because the use of NDR has increased the bonding strength of fibers. The experimental values for Tensile Strength, Shear Strength, and Flexural Strength are shown in Table 16.

Table 15.Predicted and Experimental results

Design Variables	**Initial Setting**	**Predicted value**	**Experimental Value**
Optimal variables	A3B2C4D2	A2B2C4D1	A2B2C4D1
StSq	GGCG	GCGG	GCGG
StAn	45	45	45
Re	NDR	NDR	NDR
Th	0.3	0.2	0.2
Grey Relational Grade	0.866	0.878	0.875
Improvement of the GRG=1.366%			

Table 16 Experimental test values for TS, SS and FS

	TS	**SS**	**FS**
Experimental Value-Trail No.17 (MPa)	505.23	248.96	349.56

7. Scanning Electron Microscope (SEM) analysis:

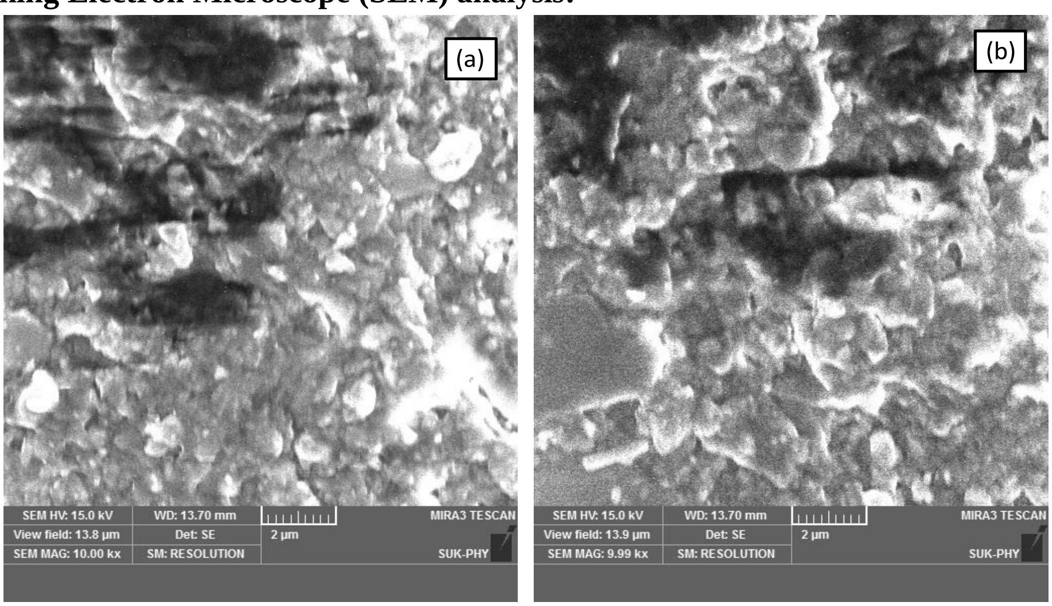


Fig.14 FESEM Images of (a) Initial setting sample (b) Validation test sample

The surface morphology of the Initial setting sample and Validation test sample were investigated using a Mira-3, Tescan, Brno-Czech Republic, Field Emission Scanning Electron Microscope (FE-SEM). Fig. 14 shows the FESEM images of (a) Initial setting sample (b) Validation Test sample recorded with 10 kx magnification. In FESEM images the grain-like morphology was observed in the samples. The crack-free and densely packed structures were observed in samples. The grain size of the Initial setting sample was about 2 μm whereas for the Validation Test sample it was observed that 1.5 μm. In Fig. (b), the well-interconnected grains were observed than Fig. 14(a). Hence the GRG value was increased by 1.366%.

8. Conclusions:

In this research work, the effect of design variables such as stacking sequence, stacking angle, types of resins (including NDR) and thickness on mechanical properties (tensile strength, shear strength, and flexural strength) of hybrid composite laminates has been experimentally investigated. The Taguchi method consolidated with GRA was used to optimize to identify design variable setting for maximum tensile, shear, and flexural strengths of hybrid composite laminates. As compared with the results obtained [30] by the GRA method for metal composites, in this research the more accurate and robust results were obtained.

Based on the results of experimental investigation and optimization, the following conclusions are drawn

1) From the experimental analysis and optimization study, it was seen that the NDR gives excellent bonding strength of fibers resulting in enhanced mechanical properties of hybrid composite laminates variable
2) The ANOVA at 95% confidence level illustrates that the resin is the most significant variable for Tensile and Flexural strength with 55.23% and 75.55 % contribution respectively. Whereas the stacking angle is the most significant variable for shear strength with a contribution of 53.27%.
3) The results of ANOVA interpret that the maximum contribution to GRG was by resin (82.11%) and pursue in abating order by stacking angle (11.60%), stacking sequence (0.486%) and laminate thickness (0.0001%). Hence resin was identically the most significant design variable. The stacking angle, stacking sequence, and thickness were the nonsignificant design variables.
4) The validation test indicated that there is an enhancement in the overall GRG at an optimal level of design variables by 1.366% Therefore, using the GRA approach of analysis; design variables have been successfully optimized to achieve enhanced mechanical properties of hybrid composite laminates.

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