Optimization of Design Variables for Carbon/Glass Hybrid Composites Laminates using the Taguchi Technique.

Abstract:

Purpose: The intent of this investigation is to analyze the significance of disparate design variables on the mechanical properties of the composite laminate. Four design variables such as stacking sequence, stacking angle, types of resins, and thickness of laminate have been chosen to analyze the impact on the mechanical properties of a composite laminate. The detailed investigation is carried out to analyze the effect of a carbon layer in stacking sequence, to investigate the impact of various resins on the fastening strength of fibers, stacking angles of the fibers and the thickness of the laminate. The impact of the above-mentioned design variables has been scrutinized on tensile strength, shear strength, and 3-point flexural strength. Carbon and glass fibers are known for their lightweight to strength ratio with outstanding mechanical properties.

Design/Methodology/Approach: The Taguchi approach has been adopted to detect the most significant design variable for optimum mechanical properties of the hybrid composite laminate. For this intend, L_{16} orthogonal array has been composed in statistical software Minitab 17. To investigate an effect of design variables on mechanical properties, Signal to Noise (S/N) ratio plots were developed in Minitab. The numerical analysis was done by using the Analysis of Variance (ANOVA).

Findings: The single parameter optimization gives the optimal combination $A_1B_1C_4D_2$ (i.e. stacking sequence C/G/G/G, stacking angle is 0^0, the type of resin is Newly Developed Resin NDR and laminate thickness is 0.3cm) for Tensile strength, $A_4B_2C_4D_2$ (i.e. stacking sequence G/G/G/C, stacking angle is 45^0, the type of resin is NDR and laminate thickness is 0.3cm) for shear strength, $A_2B_3C_4D_2$ (i.e. stacking sequence G/C/G/G, stacking angle is 90^0, the type of resin is NDR and thickness is 0.3cm) for flexural strength. The types of resins and stacking angles are the most significant design variables on the mechanical properties of the composite laminate.

Originality/Value: The novelty in this study is the development of new resin called Newly Developed Resin (NDR) from polyethylene and polyurea group. The comparative study was carried out between NDR and three conventional resins (i.e. polyester, vinyl ester, and epoxy). The NDR gives higher fastening strength to the fibers. Field Emission Scanning Electron Microscope (FE-SEM) images illustrate the better fastening ability of NDR compared with epoxy. The NDR provides an excellent strengthening effect on the RCC beam structure along with carbon fiber. (Fig.2)

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

1. Introduction:

Composite materials are widely used in modern engineering fields like aerospace, automotive, marine, defense, drilling, biomedical, etc. due to their attractive properties such as high specific modulus, high specific strength, high resistance to corrosion, low weight. (Huda et al., 2007; Cheon et al., 1999; Saha et al., 1996; Stickel and Nagarajan, 2012; Pickering et al., 2016) The mechanical properties of composite material laminate are influenced by the nature of fibers, type of resin, stacking angle, stacking sequence, and fiber volume percentage. The distinct fibers like carbon fiber, glass fiber, bamboo fiber, Cellulose fiber, etc. were used to investigate the impact on mechanical properties. (He et al., 2017; Bhagat et al., 2014; Khalil et al., 2012; Xie et al., 2010). The glass fibers are well known for their lower cost and carbon fibers are identified for its high strength to weight ratio. Some researchers have analyzed the mechanical behavior of fiber metal laminate (FML). They have used the titanium, aluminum metal to prepare hybrid composite structure with carbon and glass fiber with epoxy resin. (Sun et al., 2019; Sambran et al., 2019). The tensile strength and elastic modulus of Zn-Al alloy were improved after the reinforcement of carbon fiber (Xinwei et al., 2019). A lot of research was carried out on the mechanical properties of the fiber-resin composite. Aramid fibers with phenol-formaldehyde and polyvinyl butyral (PVB) resins have greater tensile strength and modulus than nylon 66. (Morye et al., 2000). Epoxy resin gives better mechanical properties with E-glass carbon than the phenolic resin (Wong et al., 2001). The pairing effect for the tensile strength of glass and aramid fiber with carbon fiber was investigated and resulted in a nonsignificant effect of introducing carbon fiber in the laminates structure. (Song, 2015). The comparative study of the effect of epoxy resin and polyester resin with natural fibers on tensile strength resulted in the significant effect of resins on the strength of fibers. (Oliveira et al., 2017; Maciel et al., 2018). Investigating the effect of different stacking sequences of glass and carbon fiber on tensile, flexural and impact strength of laminates for marine applications, emanated the increment in tensile strength by 14% and flexural strength by 43% of the hybrid composite compared with the plain Glass Fiber Reinforced Polymer Composites (GFRPC). (Lokman, 2018; Dipak Kumar and Ramesh Kumar, 2019; Subagia, 2014). The multi-objective robust optimization to optimize the cost and weight for unidirectional glass/carbon fiber structure under the flexural loading condition was done by using a posteriori approach. (Kalantari et al. 2016; 2017). Taguchi technique was used for the optimization of tribological properties of nano clay/epoxy/ glass fibers (Senthil Kumar et al., 2015).

The investigation of the effect of the stacking angle on the strength of fibers also can be done by using the FEA approach (Patil et al. 2012). Polyurethane (PU) has a different range of applications due to its environment-friendly properties and the possibility of new research in the synthesis process. The versatile applications of PU in the field of biomedical, building and construction, textile industry due to its admirable properties like hardness, elongation, strength, and modulus. There is a lot of research carried out in the development of a synthesis group of resin-like PU. (Akindoyo et al. 2016; Ionescu et al. 2007; Howard et al.2002) The synthesis of NDR has been composed based on this literature study.

From this detailed literature review, it is seen that many researchers analyzed the effect of single design variable but a little amount of work is done 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 done.

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 significantly affect the mechanical properties of hybrid composites. For this purpose, the Taguchi approach is used to identify the optimum combination of design variables.

Also, the purpose of this work is to investigate the effect of newly developed resin (NDR) on the fasting strength of fibers compared with other resin. Fig.1 gives a clear idea about the stacking angle and stacking sequence used to investigate the effect of these variables on the strength of the fiber. In Fig.2 the practical application of NDR along with carbon fiber has been shown used to strengthen the RCC Beam structure.

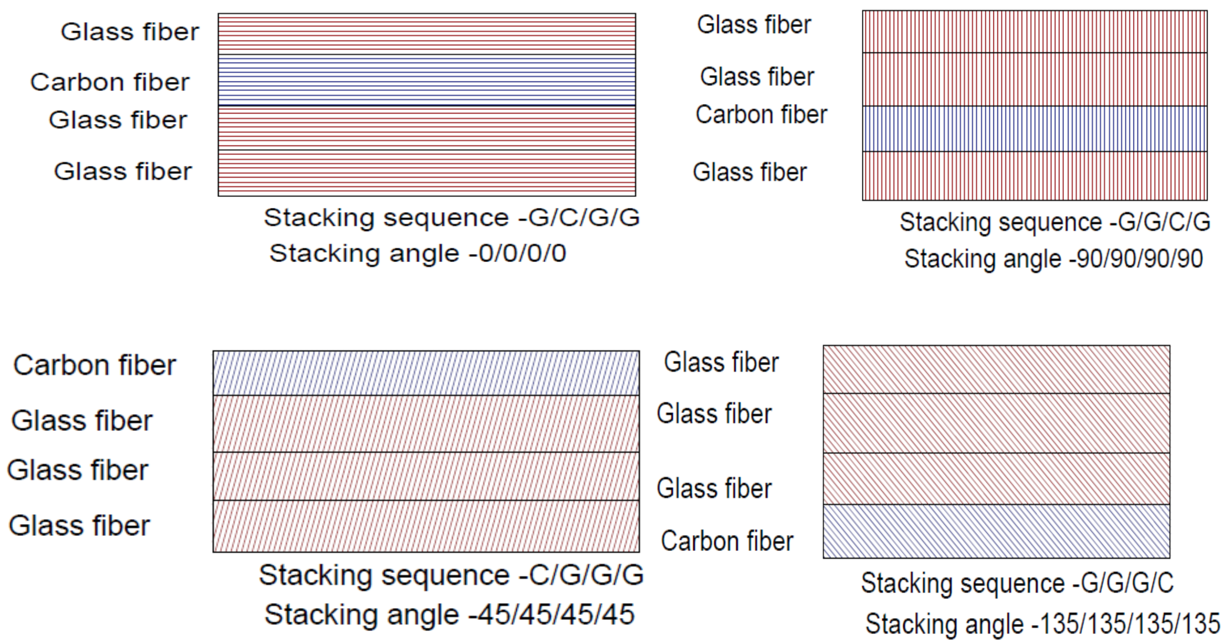

Fig.1 The Schematic diagram with different stacking angles and stacking sequences

Fig.2 RCC beam strengthening with Carbon fiber-NDR matrix

2. Design variables:

From the brief literature survey, the four design variables such as stacking sequence, stacking angle, types of resins and laminate thickness has been selected for further investigation. The details of each design variable are as follows.

a) Fibers:

For the sample preparation and to analyze the effect of stacking sequence two fibers were selected i.e. 200 GSM Carbon fiber and 900 GSM Glass fiber. The mechanical properties of these fibers are given in Table 1. These properties are obtained from SP Concare Pvt. Ltd. Pune, India.

Table 1. Mechanical properties of glass and carbon fiber

Sr.No.	Technical Data of fiber	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:

Resins play an important role in the bonding strength of the fibers. So types of resins are one of the crucial variables in the design. To investigate the impact of resin on mechanical properties of composite laminate four different resins were selected. Three resins are traditional resins i.e. epoxy, vinyl ester, and polyester and the fourth one is the new resin called Newly Developed Resin (NDR) cultivated from polyethylene and polyurea group. The NDR has been developed in SP Concare Pvt.Ltd. Sangli. (Maharashtra, India). The composition of NDR is presented in Fig. 3. The detailed formulation and contents to prepare a new resin are given in Table 2.

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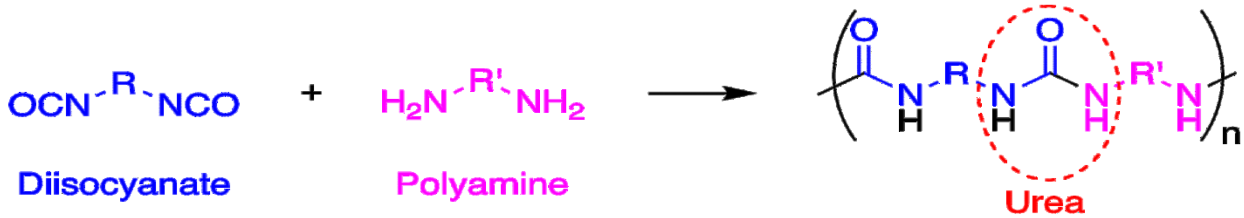

Fig.3 Synthesis of NDR

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

c) Stacking Angle:

The stacking angle is one of the important variables which are affecting the mechanical properties of the composite laminate. To analyze the exact influence of stacking angle on the strength of laminate, four stacking angles 0^0, 45^0, 90^0 and 135^0 of carbon and glass fibers were selected.

d) Stacking Sequence:

In this work, to investigate the impact of the carbon layer on the mechanical strength of the hybrid composite, two fibers were selected i.e. Glass and Carbon fibers.

3. Design of Experiments using Taguchi Method

The trustworthiness and behavior of any component which is manufactured from composite material depend on the mechanical and dynamic properties of the laminate. The mechanical and dynamic properties of composite laminate are strongly affected by the design variables like stacking sequence, stacking angle, the fastening strength of resin and thickness of the laminate. An engineering approach is needed to decide the optimum combination of the above-mentioned design variables to analyze the effect on the mechanical properties of the composite laminate. Taguchi approach can be used for the optimization of design variables to determine optimum combination with less cost and a minimum number of experimental trials. The Taguchi approach depends on the technique of matrix experiments, known as orthogonal array (OA). To obtain the optimum level of each design variables the orthogonal array was selected. Taguchi approach segregates the objective function into three groups, namely, “smaller the better type”, “larger the better type” and “nominal the best type”. For composite material, the mechanical properties like Tensile strength, Shear strength, and Flexural strength are to escalate and hence ‘larger the better type’ objective function has been selected in the existing study. The selected design variables and their recognized levels as per L_{16} OA are shown in Tables 3 and 4 respectively.

Table 3.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 4.Design of Experiments using L_{16} orthogonal array

Experiment Number	Levels of Design variables			
	StSq	StAn(^{0})	Re	Th(cm)
1	C/G/G/G	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 two fibers i.e. glass and carbon, various types of resins (epoxy, vinyl ester, and polyester) were procured from SP Concare Pvt. Ltd. Sangli (Maharashtra India). These ingredients are used in various applications and hence selected for this research work.

The special resin known as NDR was taken for comparative analysis and developed in SP Concare Pvt. Ltd. Sangli (Maharashtra India)

4.2 Preparation of hybrid composite

The hand layup method was used to prepare the hybrid composite laminates. The fibers were imbricate layer by layer and immerse with the resins in open mold and the curing was executed at ambient temperature. A vacuum pump was used to remove air bubbles. The components were fabricated according to the orthogonal array.

4.3 Testing for Mechanical Properties:

4.3.1 Tensile Test:

To fabricate the hybrid composite specimen for tensile test the ASTM standard D3039 was used.

According to the ASTM standard, the size of the specimen is 250x25 mm. To conduct the tensile test on a hybrid composite specimen universal testing machine (UTM) of capacity 100 KN with a crosshead speed of 2 mm/min was used. The tensile test specimen and experimental setup are shown in Fig. 4.

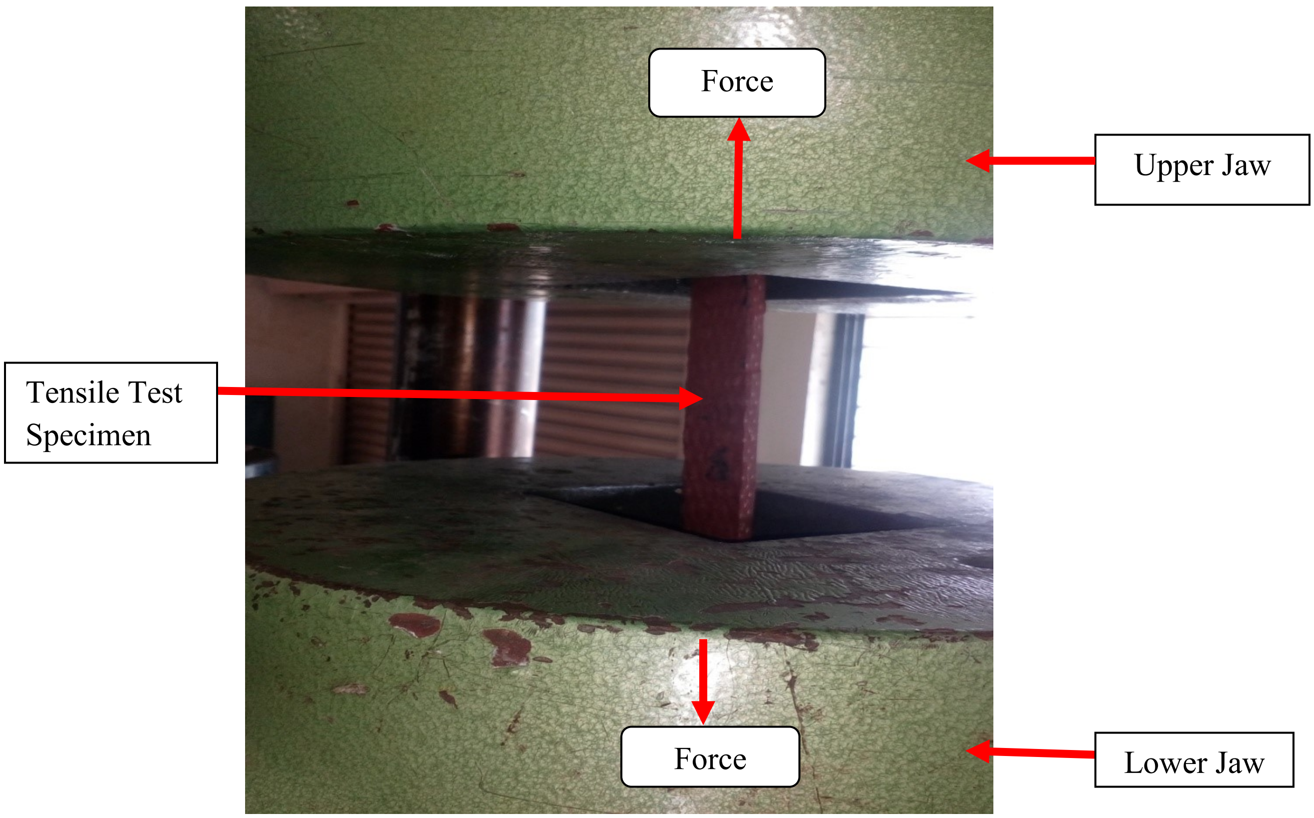

Fig.4 Setup for Tensile Test (UTM)

4.3.2 Shear Test:

The hybrid composite specimen for the shear test was fabricated according to ASTM standard D5379. The size of the specimen is 76x20mm and the experimental setup along with specimen for the shear test is shown in Fig.5.

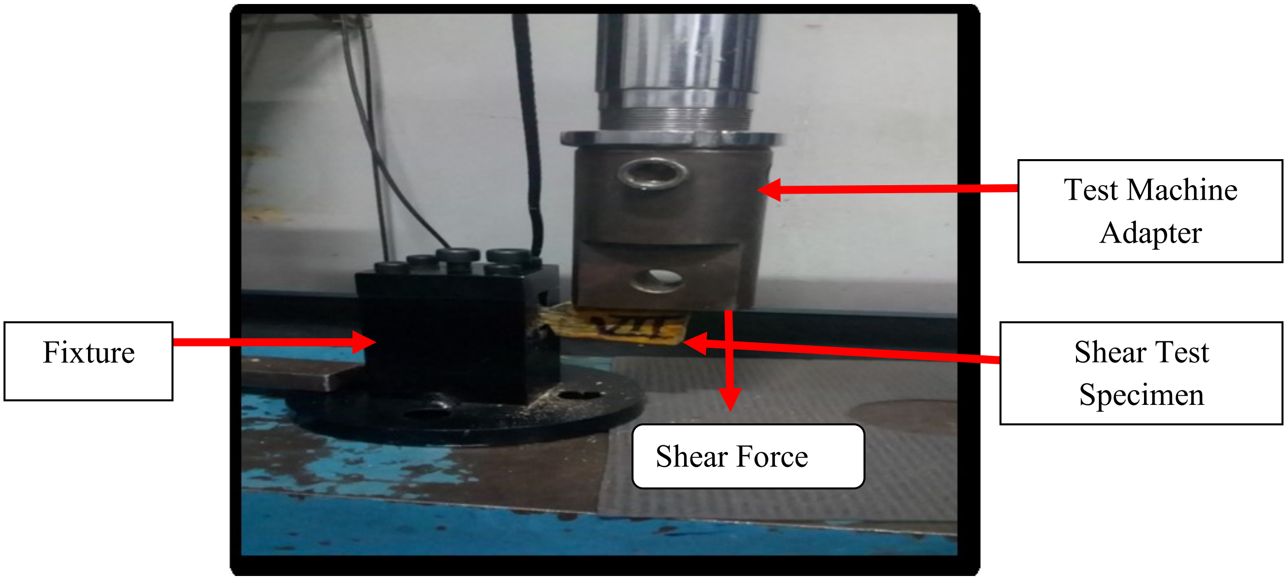

Fig.5 Setup for Shear Test

4.3.3 3-Point Flexural Test:

For the flexural test, the specimen was manufactured according to ASTM standard D790. The widths of the specimens were 12.7 mm and the span length was 16 times of thickness. A UTM with a load cell 50KN was used to carry out the test on hybrid composite laminate. The sample specimen and testing setup of the 3-point flexural test are presented in Fig.6.

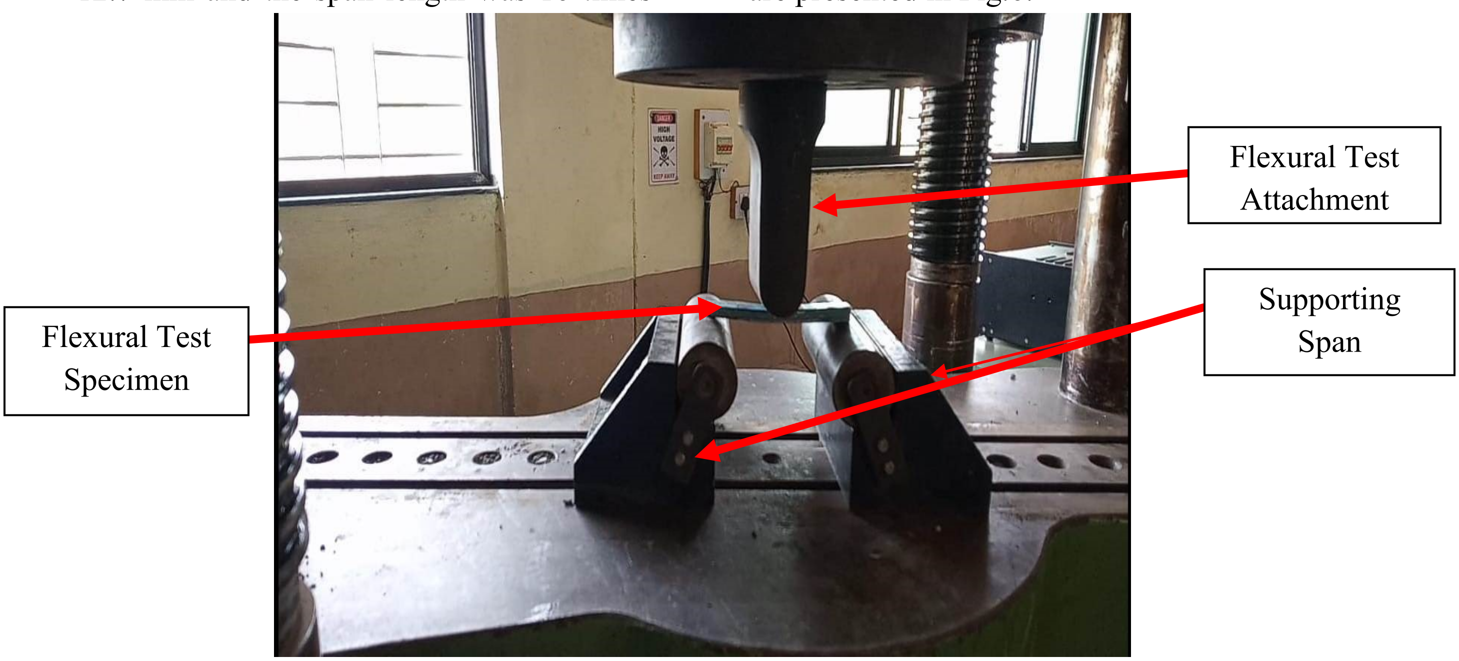

Fig.6 3-Point Flexural Test setup

5. Results and Discussions:

All experiments were carried out based on Taguchi L_{16} orthogonal array (Refer Table- 5) and the outcomes were achieved for Tensile strength (TS), Shear Strength (SS), and Flexural Strength (FS). The experimental results of mean and their associated S/N ratio values are exhibited in Table 5. The responses were scrutinized by the ANOVA and the Mean effect plots for all experimental results are developed by using the statistical software Minitab 17.

Table 5. 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):

To estimate the responses of TS, SS and FS for developing the significant and nonsignificant design variables the signal to noise (S/N) ratios are used. Greater values of TS, SS, and FS reveal an excellent strength and higher mechanical properties of composite laminates. "Larger the better type" target function was used to calculate the signal to noise ratio for TS, SS, and FS.

The S/N ratio for the "larger the better type" can be computed by using Eq. (1)

n = -10 Log_{10} [mean of sum squares of reciprocal of measured data]

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

Where y_j is response value

All the results were secured for L_{16} orthogonal array for the experimental tests at a 95% confidence level and it was statistically evaluated using ANOVA. The effects of selected design variables were assessed based on it. P-value enacts whether the design variables are significant or insignificant at an appropriate confidence level. For a 95 % confidence level, P-value must be less than 0.05 for the significant variable. ANOVA diagnoses the influence of an individual variable on the mechanical properties of the hybrid composite laminate.

5.1.1 Analysis of Tensile Strength:

ANOVA Table 6 shows that the Stacking angle and type of resin used are the most significant design variables with a contribution of 30.21% and 55.23% respectively on the tensile strength of hybrid composite laminates. The percentage contribution of the stacking sequence is 6.88% and the contribution of thickness is negligible on tensile strength. As per P-Value, both these variables are insignificant. The interaction effect of stacking sequence and laminate thickness shows a significant effect with 0.030<0.05 P-value on TS. Fig. 13 exhibits the interaction plot of stacking sequence vs. laminate thickness. The percentage error is below 8%.

Table 6. 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	
StSq*Th	3	-	260308	86769.4	5.01	0.030	-	Significant
Error	5	32237	32237	6447			7.51	
Total	15	429084						
S=80.2956	R-Sq=92.49%		R-Sq(adj)=77.46%					

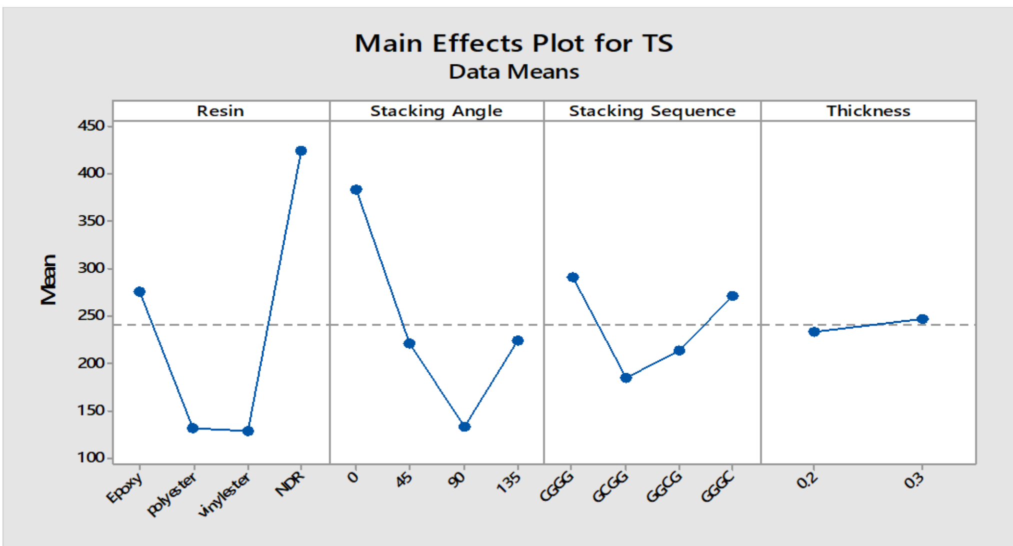

Fig.7 Main effect plot for Tensile Strength

Fig. 7 shows that the NDR resin, 0^0 stacking angle, C/G/G/G stacking sequence and 0.3 cm thickness give the higher value of Tensile strength for hybrid composite laminates.

5.1.2 Analysis of Shear Strength:

ANOVA Table 7 indicates that the Stacking Angle and type of resin used are the most significant design variables with the contribution of 53.27% and 43.32% respectively on the shear strength of hybrid composite laminates. The percentage contribution of thickness is 3.69% and the contribution of the stacking sequence is negligible on shear strength. As per P-Value, both these variables are insignificant. The percentage error is only 3.16% in the process which is considerable.

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 6) whereas for shear strength the stacking angle is the most significant factor with 53.27%. The thickness and stacking sequence are the most insignificant design variables for tensile strength and shear strength respectively. The interaction effect of stacking sequence and laminate thickness showing the nonsignificant effect on shear strength as its P-value is greater than 0.05. The fig.14 indicates the interaction effect of stacking sequence vs. laminate thickness.

Table 7.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	
StSq*Th	3	-	8408.4	2802.8	1.70	0.244	-	
Error	5	684.1	684.1	136.8			3.16	
Total	15	21646.1						
S=11.6969	R-Sq=96.84%		R-Sq(adj)=90.52%					

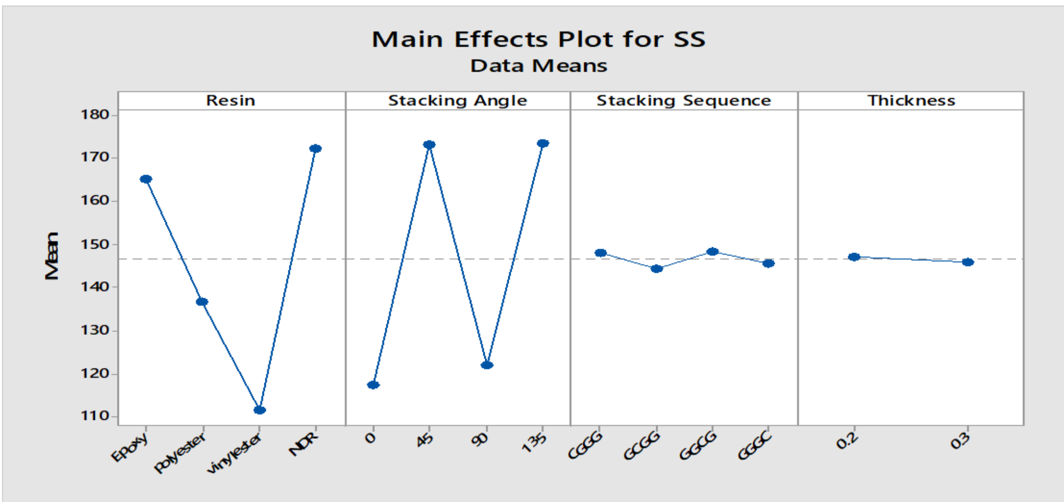

Fig.8 Main effect plot for Shear Strength

Fig.8 illustrates that the type of resin and stacking angle having a significant effect on the shear strength of the hybrid composite laminate. NDR and epoxy resin gives the higher shear strength along with 0^0 and 135^0 stacking angle.

5.1.3 Analysis of Flexural Strength:

ANOVA Table 8 signifies that the Stacking Angle and type of resin used are the most significant design variables with the contribution of 20.67% and 75.55% respectively on the flexural strength of hybrid composite laminates. The percentage contribution of the stacking sequence is 2.40% and the contribution of thickness is negligible on flexural strength. As per P-Value, both of these design variables are insignificant. But the interaction effect of stacking sequence and laminate thickness reveals a significant effect with 0.015<0.05 P-value. The fig.15 illustrates the interaction effect of stacking sequence vs. laminate thickness. The percentage error is only 1.37% in the process which is negligible.

Table 8.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	
StSq*Th	3	-	45888.6	15296.2	6.55	0.015	-	Significant
Error	5	910.3	910.3	182.1			1.37	
Total	15	66152.1						
S=13.4927	R-Sq=98.62%		R-Sq(adj)=95.87%					

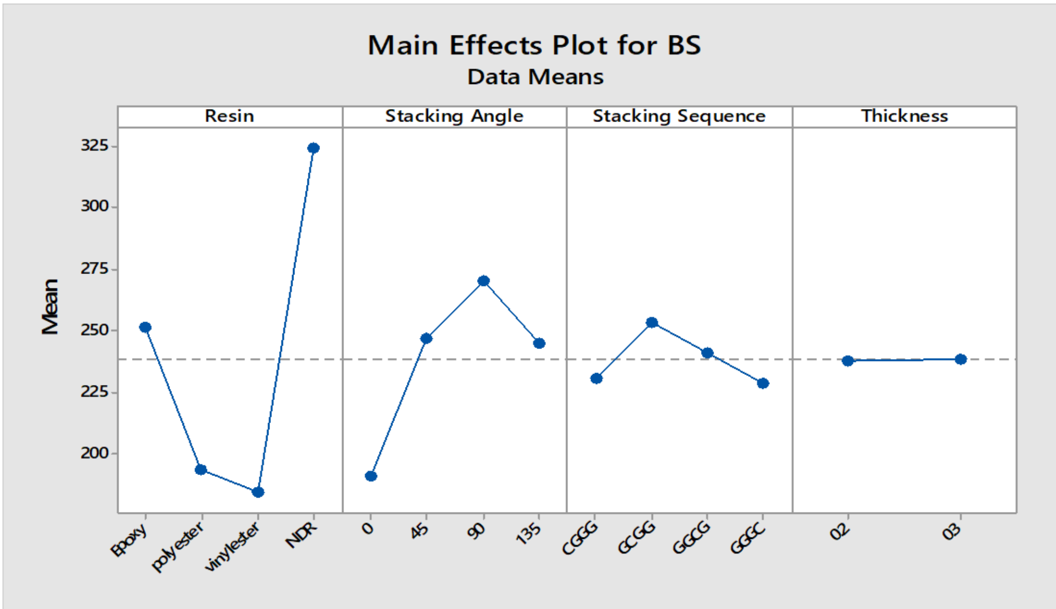

Fig.9 Main effect plot for flexural strength

Fig.9 reveals that NDR resin, 90^0 stacking angle, G/C/G/G stacking sequence gives higher flexural strength of the hybrid composite laminate. Whereas the effect of thickness laminate on flexural strength is negligible.

5.2 Interaction Plots

Fig. 10, 11 and 12 exhibit the interaction plots for TS, SS, and FS respectively. From table 6 it is noticed that the TS is supremely affected by the resin and stacking angle with low impact of stacking sequence. Fig.10 (A), (B) and (C) indicate the relation between resins vs. stacking angles, resins vs. stacking sequence and stacking angle vs. stacking sequence respectively. Fig.10 (A) reveals that for all resins the stacking angle 0^0 gives the higher tensile strength. Also, Fig.10 (B) shows that the NDR gives good tensile strength for C/G/G/G stacking sequence. Fig.10 (C) indicates that the insignificant effect of stacking sequence on tensile strength. Fig.11 (A), (B) and (C) indicate the relation between resins vs. stacking angles, resins vs. thickness and stacking angle vs. stacking thickness respectively. Fig.11 (A) illustrates that for all resins the stacking angle 45^0 and 135^0 gives the higher shear strength. Whereas Fig. 11 (B) & (C) indicate the effect of thickness with respect to resin and stacking angle is insignificant on shear strength. Fig 12 (A), (B) and (C) implies the optimized combination for flexural strength is NDR with G/C/G/G stacking sequence and 90^0 stacking angle.

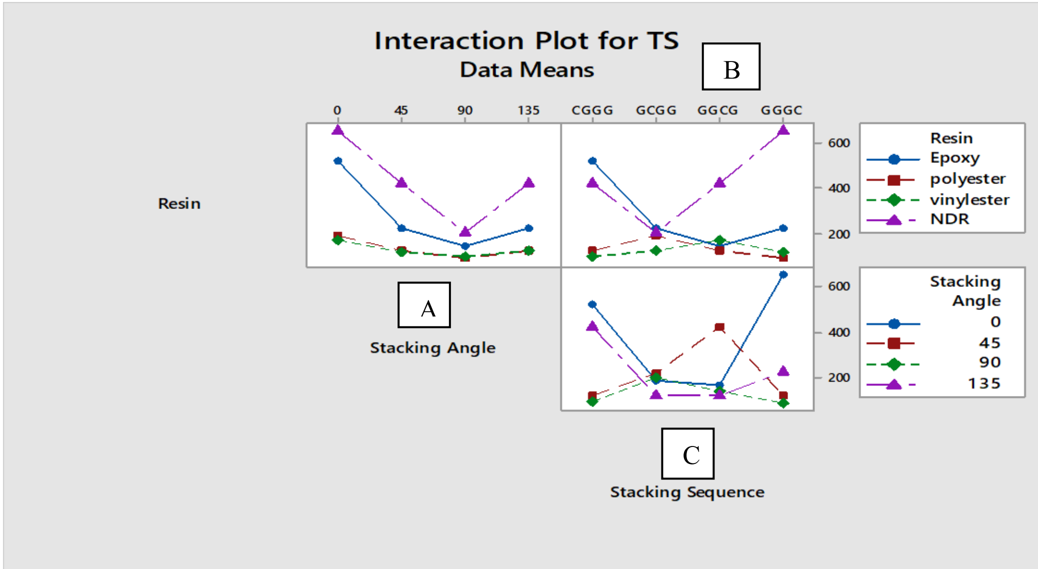

Fig.10 Interaction effect of stacking sequence, stacking angle and resin on TS

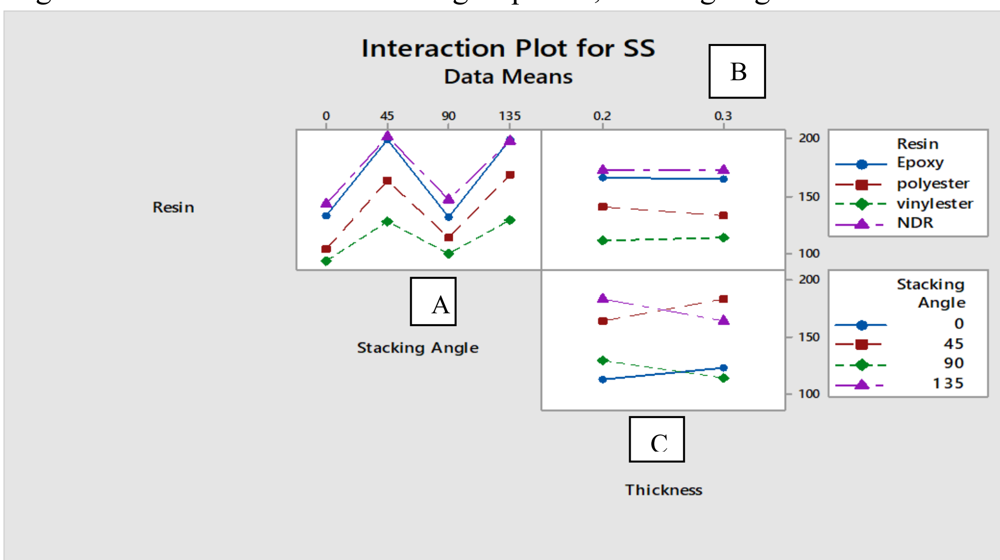

Fig.11 Interaction effect of stacking angle, resin, and thickness on SS

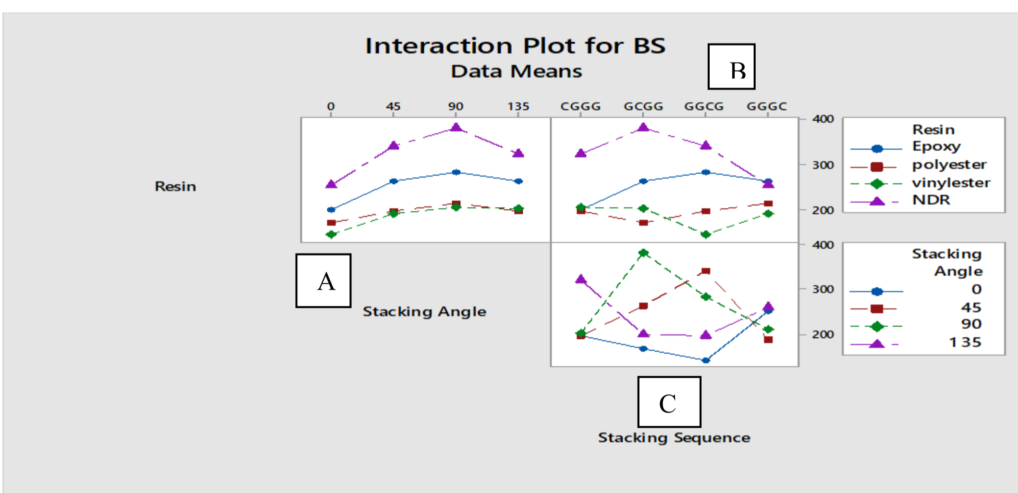

Fig.12 Interaction effect of stacking sequence, stacking angle, and resin on BS

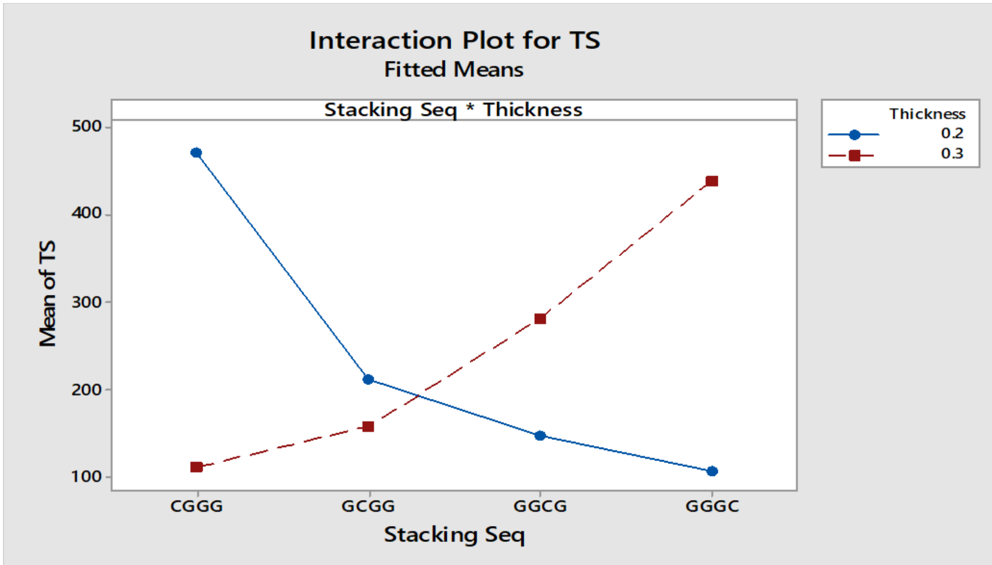

Fig.13 Interaction effect of stacking sequence vs. laminate thickness for TS

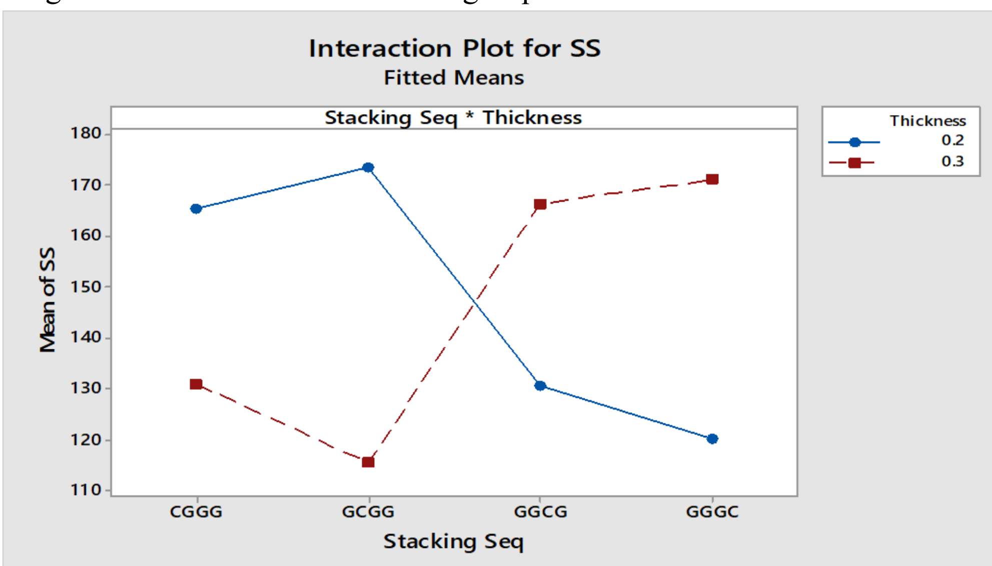

Fig.14 Interaction effect of stacking sequence vs. laminate thickness for SS

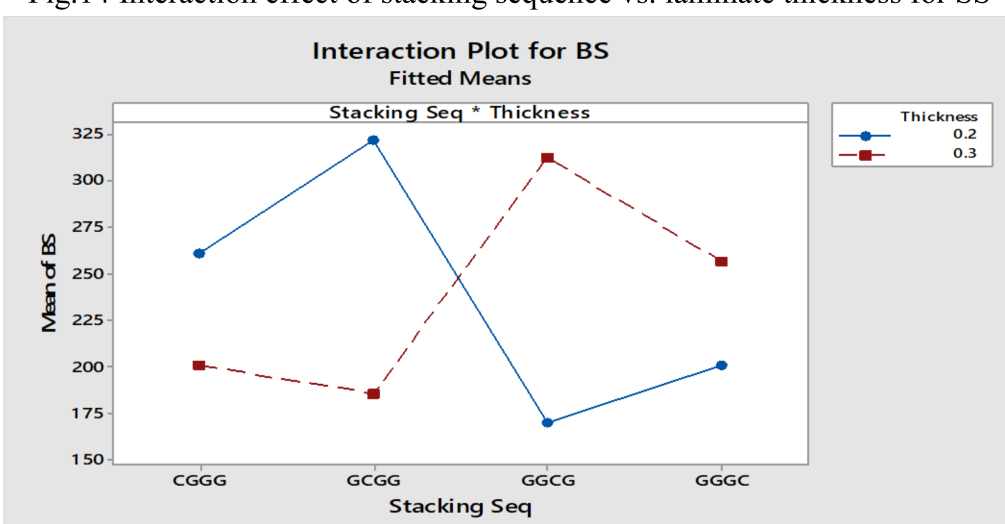

Fig.15 Interaction effect of stacking sequence vs. laminate thickness for BS

5.3 Evaluation of the S/N ratio for the optimal design

The mean response refers to the average values of mechanical properties for each design variable at different levels are indicated in Fig.5-7. The average values of S/N ratios for TS, SS, and FS were obtained separately and presented in Tables 9, 10 and 11 respectively. As per the Taguchi method, the value of the S/N ratio is directly proportional to overall performance. Hence the factor levels are selected for the highest S/N ratio value. Based on S/N ratio evaluation and ANOVA, the optimal input variables for TS are stacking sequence at level 1, stacking angle at level 1, resin at level 4 and thickness at level 2 (Refer Table 9). Table 10 indicates that optimal input variables for SS are stacking sequence at level 4, stacking angle at level 2, resin at level 4 and thickness at level 2. Table 11 reveals that the combination of design variables for FS is stacking sequence at level 2, stacking angle at level 3, resin at level 4 and thickness at level 2 gives the maximum value for FS. The above combinations of design variables give the highest values for TS, SS, and FS respectively.

Table 9.Response table for S/N ratios for TS

Level	**StSq**	**StAn**	**Re**	**Th**
1	188.477	200.813	188.82	365.6
2	180.813	184.464	166.63	366.587
3	178.702	165.471	167.984	
4	184.195	181.439	208.753	
Δ	9.775	35.342	42.123	0.987
Rank	3	2	1	4

Table 10.Response table for S/N ratios for SS

Level	**StSq**	**StAn**	**Re**	**Th**
1	172.507	167.049	178.512	347.607
2	173.498	183.913	169.397	347.905
3	173.518	166.569	165.223	
4	175.989	177.981	182.38	
Δ	3.482	17.344	17.157	0.298
Rank	3	1	2	4

Table 11.Response table for S/N ratios for FS

Level	**StSq**	**StAn**	**Re**	**Th**
1	189.906	182.9	195.149	380.112
2	193.186	193.56	182.735	381.54
3	186.385	195.091	180.955	
4	192.175	190.101	202.813	
Δ	6.801	12.191	21.858	1.428
Rank	3	2	1	4

5.4. Analytical Calculations for Forces and Moments:

The following steps are carried out to calculate the analytical forces and moments for composite laminate structure.

a) Unidirectional Continuous Fiber 0^0 Lamina

For Longitudinal Modulus

$$E_{11} = E_f V_f + E_m V_m$$

Where, E_f = Modulus of Fiber

E_m= Modulus of Matrix

V_f= Volume of Fiber in %

V_m= Volume of Matrix in %

& Major Poisson's Ratio

$$\upsilon_{12} = \upsilon_f V_f + \upsilon_m V_m$$

Where, υ_f = Poisson's ratio of Fiber

υ_m = Poisson's ratio of Matrix

For Transverse Modulus

$$E_{22} = \frac{E_f E_m}{E_f V_m + E_m V_f}$$

& Minor Poisson's Ratio

$$\upsilon_{21} = \frac{E_{22}}{E_{11}} \upsilon_{12}$$

In-Plane Shear Modulus

$$G_{12} = G_{21} = \frac{G_f G_m}{G_f V_m + G_m V_f}$$

Where, G_f= Shear Modulus of Fiber

G_m=Shear Modulus of Matrix

From the above step, the property of each composite lamina of either Glass Fiber/resin matrix or Carbon Fiber/resin matrix has been calculated

STEP-II

b) The properties calculation for Unidirectional Continuous Angle Ply Laminate

$$\frac{1}{E_{xx}} = \frac{\cos^4\theta}{E_{11}} + \frac{\sin^4\theta}{E_{22}} + \frac{1}{4}\left(\frac{1}{G_{12}} - \frac{2\upsilon_{12}}{E_{11}}\right) \mathrm{Sin}^2 2\theta$$

$$\frac{1}{E_{yy}} = \frac{\sin^4\theta}{E_{11}} + \frac{\cos^4\theta}{E_{22}} + \frac{1}{4}\left(\frac{1}{G_{12}} - \frac{2\upsilon_{12}}{E_{11}}\right) \mathrm{Sin}^2 2\theta$$

$$\frac{1}{G_{xy}} = \frac{1}{E_{11}} + \frac{2\upsilon_{12}}{E_{11}} + \frac{1}{E_{22}} - \left(\frac{1}{E_{11}} + \frac{2\upsilon_{12}}{E_{11}} + \frac{1}{E_{22}} - \frac{1}{G_{12}}\right) \mathrm{Cos}^2 2\theta$$

$$\upsilon_{xy} = E_{xx}\left[\frac{\upsilon_{12}}{E_{11}} - \frac{1}{4}\left[\frac{1}{E_{11}} + \frac{2\upsilon_{12}}{E_{11}} + \frac{1}{E_{22}} - \frac{1}{G_{12}}\right] \mathrm{Sin}^2 2\theta\right]$$

$$\upsilon_{yx} = \frac{E_{yy}}{E_{xx}} \upsilon_{xy}$$

Where, E_{11}, E_{22}, υ_{12} & G_{12} are calculated using step I

Step-III

Then factor [Q] is calculated as follows

$Q_{11} = \frac{E_{11}}{1-\upsilon_{12}\upsilon_{21}}$ -------------------for 0^0 lamina

$Q_{11} = \frac{E_{xx}}{1-\upsilon_{xy}\upsilon_{yx}}$ ----------------- for θ^0 lamina

$Q_{22} = \frac{E_{22}}{1-\upsilon_{12}\upsilon_{21}}$ ------------------for 0^0 lamina

$Q_{22} = \frac{E_{yy}}{1-\upsilon_{xy}\upsilon_{yx}}$ -------------------for θ^0 lamina

$Q_{12} = \frac{\upsilon_{12}E_{22}}{1-\upsilon_{12}\upsilon_{21}}$ ------------------for 0^0 lamina

$Q_{12} = \frac{\upsilon_{xy}E_{yy}}{1-\upsilon_{xy}\upsilon_{yx}}$ -------------------for θ^0 lamina

$\upsilon_{21} = \frac{E_{22}}{E11} \upsilon_{12}$---------------------for 0^0 lamina

$\upsilon_{21} = \frac{E_{yy}}{Exx} \upsilon_{xy}$---------------------for θ^0 lamina

$Q_{66} = G_{12}$----------------------for 0^0 lamina

$Q_{66} = G_{xy}$-----------------------for θ^0 lamina

STEP-IV

The factor $[\overline{Q}]$ has been calculated as follows:

$\overline{Q}_{11}= Q_{11}\cos^4\theta + 2(Q_{12} + 2Q_{66}) \sin^2\theta\cos^2\theta + Q_{22}\sin^4\theta$

$\overline{Q}_{12}= Q_{12}(\cos^4\theta+\sin^4\theta) + (Q_{11} + Q_{22} - 4Q_{66}) \sin^2\theta\cos^2\theta$

$\overline{Q}_{22}= Q_{11}\sin^4\theta + 2(Q_{12} + 2Q_{66}) \sin^2\theta\cos^2\theta + Q_{22}\cos^4\theta$

$\overline{Q}_{16}= (Q_{11}-Q_{12} - 2Q_{66})\sin\theta\cos^3\theta + (Q_{12}-Q_{22} + 2Q_{66})\sin^3\theta\cos\theta$

$\overline{Q}_{26}= (Q_{11}-Q_{12} - 2Q_{66})\sin^3\theta\cos\theta + (Q_{12}-Q_{22} + 2Q_{66})\sin\theta \cos^3\theta$

$\overline{Q}_{66}= Q_{66}(\cos^4\theta+\sin^4\theta) + (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66}) \sin^2\theta\cos^2\theta$

It is calculated that for fiber orientation angle θ &-θ

$\overline{Q}_{11}(-\theta) = \overline{Q}_{11}(\theta)$

$\overline{Q}_{12}(-\theta) = \overline{Q}_{12}(\theta)$

$\overline{Q}_{22}(-\theta) = \overline{Q}_{22}(\theta)$

$\overline{Q}_{66}(-\theta) = \overline{Q}_{66}(\theta)$

$\overline{Q}_{16}(-\theta) = \overline{-Q}_{16}(\theta)$

$\overline{Q}_{26}(-\theta) = -\overline{Q}_{26}(\theta)$

STEP V

The elements in matrices [A][B][D] are calculated from the following relation

$$Amn =\sum_{j=1}^{N}(\bar{Q}mn)_j\ (h_j-h_{j-1})$$

$$Bmn=\frac{1}{2}\sum_{j=1}^{N}(\overline{Q_{mn}})_j\ (h^2{}_j - h^2{}_{j-1})$$

$$Dmn=\frac{1}{3}\sum_{j=1}^{N}(\overline{Q_{mn}})_j\ (h^3{}_j - h^3{}_{j-1})$$

Where, [A] = extensional stiffness matrix (unit N/m)

$$A = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{12} & A_{22} & A_{26} \\ A_{16} & A_{26} & A_{66} \end{bmatrix}$$

[B] =coupling stiffness matrix for the laminate [unit N]

$$B = \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \end{bmatrix}$$

[D]=Bending stiffness matrix for laminate [unit N-m]

$$D = \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix}$$

$$N_{xx}=[A]\varepsilon_{xx}^{0}+[B]K_{xx}$$

$$M_{xx}=[B]\varepsilon_{xx}^{0}+[D]K_{xx}$$

Where, N_{xx}=Normal Force resultant in the x-direction

M_{xx}= Bending Moment resultant in xy direction

ε_{xx}^{0} =Midplane normal strains in laminate

K_{xx} =Bending Curvature of laminate

From the above analytical steps, the forces and moments are calculated and compared with experimental results which are presented in Table 13.

5.5. Corroboratory experiments

Corroboratory experiments were composed as per the optimum levels anticipated by analysis of mean (ANOM).

The experiments were executed to confirm the optimization of L_{16} Orthogonal Array. Table 12 indicates the predicted and experimental values for TS, SS, and FS. It can be seen that an error between the experimental and predicted values is less than 5% for TS, SS, and FS. It also endorses that the predicted values of optimized mechanical properties for various design variables are in close agreement with those obtained by experimentally.

Table 12. Corroboratory results for TS, SS, and FS

Level	TS	SS	FS
	$A_1B_1C_4D_2$	$A_4B_2C_4D_2$	$A_2B_3C_4D_2$
Predicted	680.54	262.56	394.21
Experimental	655.90	256.23	386.70
Error (%)	3.620	2.410	1.905

Table 13.Comparison of Analytical and Experimental results for Force and Moments

Expt. No.	Tensile Test		Shear Test		Flexural Test	
	Analytical N_{xx}(N)	Experimental N_{xx}(N)	Analytical N_{xx}(N)	Experimental N_{xx}(N)	Analytical M_{xx}(N-m)	Experimental M_{xx}(N-m)
1	112.07	103.80	23.36	21.16	29637.20	26944.98
2	50.20	46.12	42.16	39.12	50006.32	47449.72
3	34.32	30.69	34.32	31.34	89630.61	86532.72
4	70.52	67.65	50.21	47.86	91202.32	88163.40
5	60.31	57.54	26.33	24.60	53623.32	51633.12
6	39.56	36.48	41.26	39.24	67069.51	64068.96
7	20.23	18.36	20.32	18.03	36823.22	34723.67
8	22.97	20.40	26.31	24.99	23520.41	20334.05
9	36.43	33.90	16.20	14.80	21232.63	19385.76
10	27.54	24.06	27.32	24.99	28320.36	25630.92
11	32.33	29.85	25.63	23.62	65231.92	62362.08
12	40.07	37.08	33.32	30.79	64998.23	61417.20
13	199.20	195.27	46.31	43.08	91237.20	88270.08
14	153.22	148.70	62.32	60.29	11123.42	104247.70
15	42.23	40.18	25.52	23.53	54232.84	51708.90
16	88.23	84.52	34.20	31.73	51436.91	49541.38

6. FEA Analysis for TS, SS, and BS:

To investigate the effect of design variables on TS, SS, and BS the finite element models were developed in ANSYS 16.0. The plane 182 element was used to provoke the structure for TS and SS and shell 181 elements were used to carry out the analysis for BS. The fig.16, 17 and 18 show the simulation models with results for TS, SS and BS respectively. The developed models in FEA give closer results with experimental data.

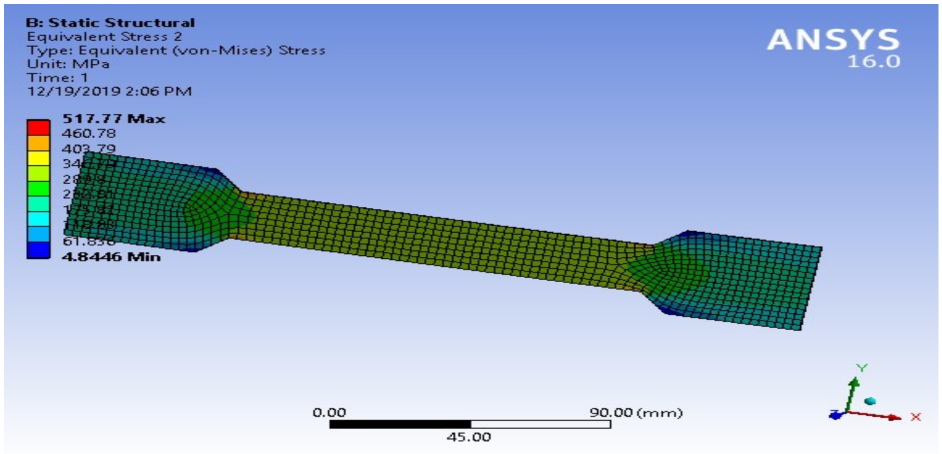

Fig.16 FEA model for Tensile Stress analysis

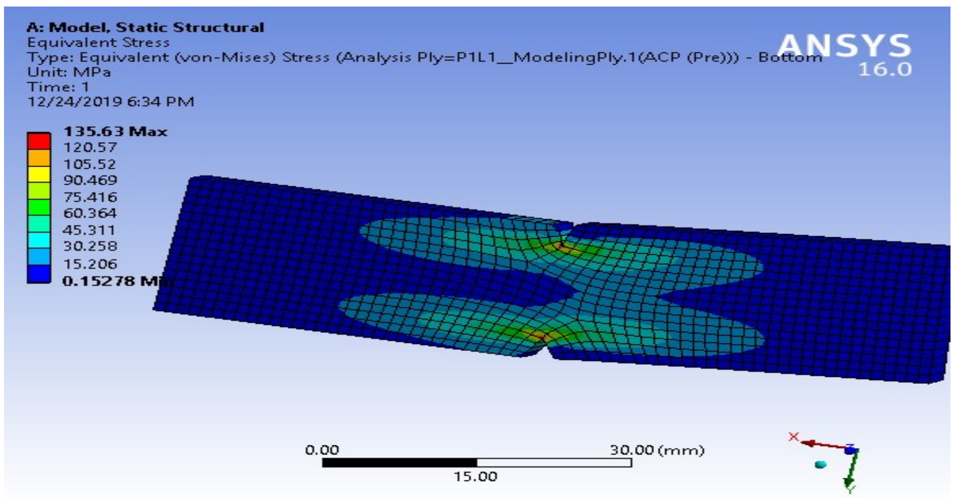

Fig.17 FEA model for Shear Stress analysis

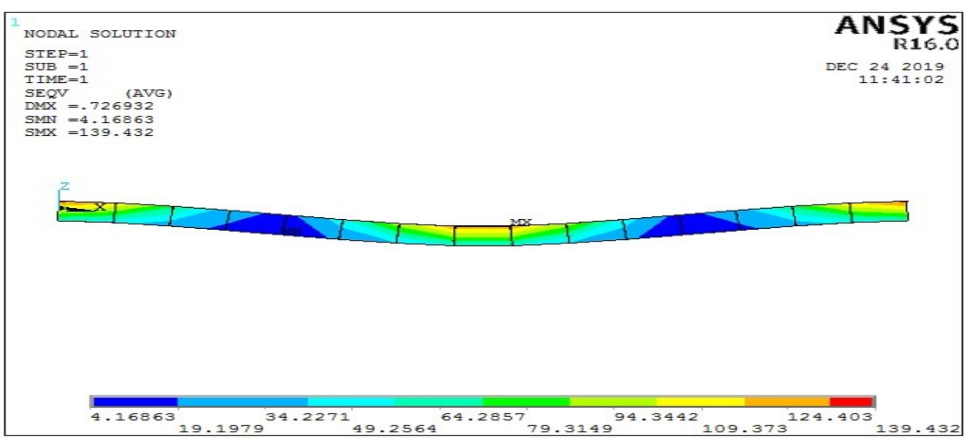

Fig.18 FEA model for Bending Stress analysis

7. Surface Morphology Study:

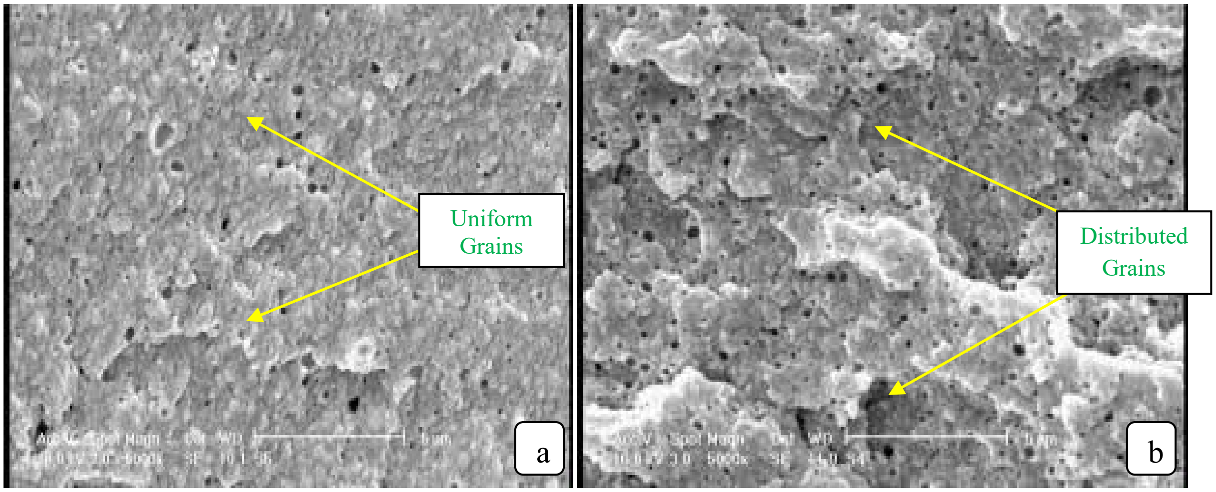

Fig.19 FESEM Images of (a) NDR sample (b) Epoxy resin

The surface morphology for the NDR sample (Fig.19 (a)) and epoxy sample (Fig.19 (b)) were interrogated using a Mira-3, Tescan, Brno-Czech Republic, and Field Emission Scanning Electron Microscope (FESEM). In FESEM images the grain-like morphology was observed in the samples with 10 kx magnification. Fig. 19(a) shows the FESEM image with uniform grains for NDR resin. The grain structure is distributed for the epoxy sample (Fig.19 (b)). This indicates the NDR gives the marvelous bonding strength of fibers than that of epoxy resin. Fig.19 (a), (b) point out the tenacity of NDR on the strength of the hybrid composite laminate.

8. Conclusions:

In this investigation, the influence of four design variables, namely, stacking sequence, stacking angle, types of resin and thickness of laminate on the mechanical properties like tensile strength, shear strength and flexural strength of composite laminate has been analyzed experimentally and optimized by using the Taguchi approach. The subsequent conclusions are drawn based on the results of experimental investigation and optimization.

1) From the experimental analysis and optimization study, it was seen that the NDR gives admirable fastening strength of fibers resulting in enhanced tensile, shear and flexural strength of hybrid composite laminates.
2) The design variables stacking angle and types of resins were the most significant factors for TS, SS, and FS with percentage contribution 30.21% and 55.23% respectively for TS, 53.27% and 43.32% respectively for SS and 20.67% and 75.55% respectively for FS.
3) An interaction plot reveals that the stacking sequence was not a significant factor but having a minor effect on TS and FS. Similarly, the thickness of laminate has a minor effect on SS.
4) The interaction effect of stacking sequence vs. laminate thickness is a

significant factor for TS and BS with P-value is less than 0.05.

5) From corroboratory experiments, the error percentage for TS, SS, and FS are 3.620, 2.410 and 1.905 respectively, which is less than the tolerable limit of 10 percent.
6) FESEM study clearly interprets the impact of resins on the bonding strength of fibers. The NDR gives a uniform grain structure than that of epoxy. Hence NDR gives higher TS, SS and FS as compared with other resins.
7) From analytical and experimental results (Table 13), the error percentage for forces and moments are below 10%.

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