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Design and analysis of gear made from natural fiber reinforced polymer matrix composite

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Abstract. This paper presents the stress analysis of spur gear made from natural fiber reinforced polymer matrix composite material. These gears provide better alternative for replacing metallic gears. In this work epoxy resin is used as matrix material. Fly ash, coir fiber and carbon nano tube are used as reinforcement materials. Response surface methodology, one of the design of experiment approaches, is used to arrive the different material combinations. Static structural analysis is performed to obtain stress distributions and deformation. Analysis of variance (ANOVA) is employed to get optimized combinations for maximum stress. Analysis reveals that these gears can be used in low strength applications.

Keywords: analysis of variance; epoxy resin; finite element analysis; natural fiber; response surface methodology

1. Introduction

Gears are commonly used for transmission of power under different loads and speeds. Gears are especially used in automotive industries, food industries, textile machines and house hold utensils. Involute spur gears with asymmetric teeth have been used for high performance applications. Polymers are used due to their advantages such as noiseless running, corrosion resistance, light weight, low co efficient friction and run without external lubrication. It can be combined with different materials for enhanced properties. Polymers have low surface energy and visco elastic properties. Polymers also reduce heat generation at contact surfaces due to their self-lubrication properties. Polymers have less weight compared to other metals due to low density which decreases maintenance and cost. These Natural fibers are from environmental waste. The use of natural fiber, from renewable and non-renewable such as oil palm, sisal, flax, and jute, is

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getting attention to produce composite materials, Fiber reinforced polymer matrix are used due to their good properties and advantages over synthetic fiber in terms of weight, cost etc. and mechanical properties such as flexural and tensile modulus, flexibility and biodegradability strength and stiffness. Kurokawa *et al*. (1999) manufactured the gear using carbon fiber (CF) reinforced poly-ether- ether-ketone (PEEK/CF). From the tests, authors concluded that the gear load capacity was varying depending on the partner gear and running conditions such as whether grease exists or not with regard to PEEK/CF gears using three kinds of CF. The gear performance of carbon fiber (CF) reinforced polymide 12 (PA12) was compared with CF reinforced polyamides such as polyamide 6 (PA6), polyamide 66 (PA66), and polyamide 46 (PA46) by Kurokawa *et al*. (2003) and from the experiments carried it was concluded that PA12/CF has the highest load capability, excellent noiseless property, and the lowest water absorption among all polyamides used. Aslantas *et al*. (2004) calculated the numerical prediction on pitting formation of spur gear made up of austempered ductile iron. Rolling and sliding contacts were considered for development of analytical model. The problem is assumed under LEFM / FEM for numerical calculation. Experimental study was carried out to determine pitting formation on tooth surface.

Taj *et al*. (2007) suggested from their investigations that Natural fiber can be employed in combination with plastics. Many types of natural fibers have been investigated for use in plastics including jute, straw, wood fiber, rice husks, wheat, barley, oats, rye, sugar cane etc. Natural fibers, when used as reinforcement, could compete with such synthetic fiber such as glass fiber. Mao (2007) suggested the new design method for the polymer composite gear based on the link between the polymer composite gears wear rate and its surface temperature. It was concluded from the test that polymer gear wear rate will be increased when load reaches a critical value.

Karaveer *et al*. (2013) presented the stress analysis of mating teeth of spur gear to find maximum contact strength in the gear teeth. The results obtained from Finite Element Analysis (FEA) were compared with theoretical Hertzian equation values. For the analysis, steel and grey cast iron were used as the materials of spur gear. Yuvaraj (2014) described the manufacturing of composite spur gears reinforced with alkali treated Lantana Camara powder with different volume fraction with unsaturated polyester resin selected as matrix material. Three spur gears with different compositions such as 5%.10% and 15% were manufactured. Cathelin *et al*. (2014) investigated the loaded behavior of gears made from glass fiber-Reinforced PA6 and presented the efficient method to predict the mechanical behavior of polyamide 6 + 30% glass fiber spur gears. It is concluded that the variation of temperature, humidity and rotation speed can have a considerable influence on displacement. Pawar *et al*. (2015) fabricated gears using steel alloy and Aluminum Silicon carbide composite. Al-SiC composite provides improved hardness and weight loss compared to steel alloys.

Ramanjaneyulu *et al*. (2017) proposed replacement of plastic gears from metallic gears. They developed the gear made up of graphene reinforced acetal polymer through injection molding process. Hejazi *et al*. (2017) introduced a new multi response surface methodology (RSM) for quality optimization in multistage systems with multiple response variables. In which, Design of Experiments (DOE) was used to identify the process parameters and their effect on the response set. Moon *et al*. (2017) studied the layout concepts and two part transfer policies in a transfer line. The first transfer policy allows the part to move next operation independently and second transfer policy allows parts for transferring for next operation when all operations in a sub-line are completed. And compared between these two different policies in different layouts having number of transfer lines and assembly operations.

Dhanushkodi and Arunagiri (2018) found that gear, made from natural fibre reinforced composite, has less tooth wear, withstand high temperature and low weight reduction while comparing to glass fiber-reinforced composite and hence recommended potential applications like noiseless and smooth operation. Nair *et al*. (2019) concluded that the Aluminium Titanium metal matrix composite is used for the manufacturing of spur gears because of its less weight, more life, withstand more load, better strength to weight ratio, better hardness. Singh *et al*. (2016) proposed Aluminium Silicon carbide composite for manufacturing of spur gears because of its reduced stress distribution, low deformation and less weight. Qrimli *et al*. (2015) concluded that carbon/epoxy and glass/epoxy composites perform better compared to jute/epoxy owing to their low stiffness. It is a viable alternative towards steel gears and COPRASS method is applied to determine the optimum material gear and it turned out to be glass/epoxy composite.

Kumar and Manoharan (2017) analyzed gear tooth contact for spur gears composite material through finite element analysis and found that the deformation of composite material gear was very less compared to steel and plastic materials. Devi (2017) concluded that short carbon reinforced gears would be a best alternative to cast iron and mild steel gears under limited load applications up to 1500 watts. Gajanan *et al*. (2020) concluded that stress values for the composite material is lesser than that of aluminum alloy for the applications in marine industries. Mahalingam *et al*. (2020) experimented the specimen by varying contents of CNT/coir fibre/fly ash with epoxy by using the response surface methodology. Optimum reinforcement parameters were obtained through a teaching–learning-based optimization algorithm. A confirmation test was also carried out to determine the shear modulus experimentally for the reinforcement parameters obtained from the optimization process.

From the literature survey, it is concluded that limited/nil attempts have been made to fabricate/analyze Gears made from green materials such as natural fiber reinforced composites. An attempt is made in this work to reinforce bio degradable/waste/recyclable materials with polymer matrix. Efforts are made to use coir fiber/carbon nano tube/Fly ash as reinforcements in epoxy polymer matrix. Response surface methodology (RSM), one of the design of experiments (DOE) approaches, is used to fabricate samples with different compositions of coir fiber, carbon nano tube and Fly ash. After evaluating the material properties of composites, it is explored to do the stress analysis of gears made from these composite materials using finite element method.

2. Methodology

Elastic properties required for the stress analysis of gears are taken from Venkatachalam *et al*. (2023) i.e., authors previous work. In this work, Epoxy resin [LY556] is used as matrix. Coir fiber (in powder form), CNT and Fly ash are used as reinforcements. The coir fiber powder is sourced from natural coconut husks, with a particle size of approximately 100-200 micrometers. CNTs, obtained from Nanoshel supplier (Punjab, India), have diameters around 10-20 nanometers and lengths of 3-8 micrometers. Fly ash is collected from coal combustion processes, with particle sizes ranging from 10-50 micrometers. Design of experiments is the statistics tool (or) technique used to evaluate the factors that control the parameters (or) group of parameters. The Central Composite Design (CCD) in Response Surface Methodology (RSM) is used as DOE tool to arrive the different combinations of samples. The parameters, such as the wt% of coir, CNT and Fly ash, are taken as the input parameters. Wt% of coir and Fly ash are taken from 0% to 2% and that of CNT is taken from 0% to 1%. The different levels of wt% and its actual values are given in Table 1.

Table 1 Different levels and wt% of Coir, CNT and Fly ash

Variables	Parameters	Levels	-2	-1	0	1	2
A	Coir	Wt % of materials in composite (actual weight in gm is given in bracket)	0 (0)	0.5 (0.091)	1 (0.182)	1.5 (0.273)	2 (0.364)
B	CNT		0 (0)	0.25 (0.0455)	0.5 (0.091)	0.75 (0.1365)	1 (0.182)
C	Fly-ash		0 (0)	0.5 (0.091)	1 (0.182)	1.5 (0.273)	2 (0.364)

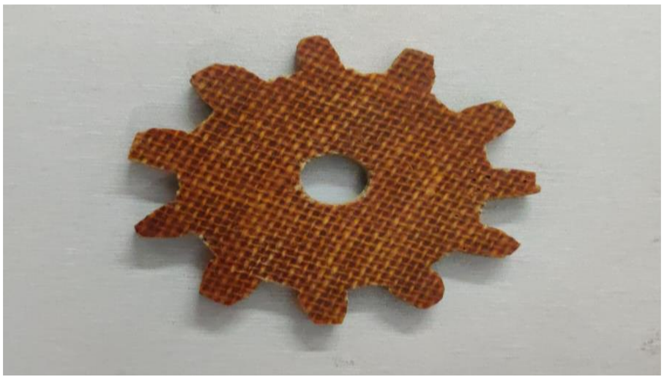

Fig. 1 Gear sample

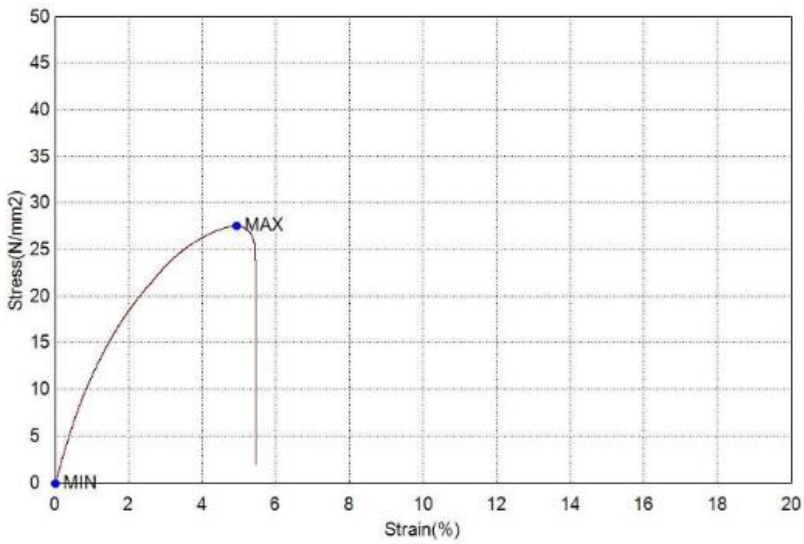

Fig. 2 Stress strain curve for sample 10

2.1 Sample preparation

The hand lay-up method is used to fabricate coir fiber powder composites for gear applications. Coir fiber powder, with a particle size of 100-200 micrometers are mixed with a polymer resin

Table 2 Different combinations of Tensile test specimens based on CCD of RSM

Exp. No	Coir		CNT		Fly ash	
	Coded	Actual	Coded	Actual	Coded	Actual
1	-1	0.091	1	0.1365	-1	0.091
2	0	0.182	0	0.091	0	0.182
3	1	0.273	-1	0.0455	-1	0.091
4	0	0.182	0	0.091	0	0.182
5	1	0.273	1	0.1365	1	0.273
6	-1	0.091	-1	0.0455	1	0.273
7	0	0.182	0	0.091	0	0.182
8	0	0.182	0	0.091	2	0.364
9	-2	0	0	0.091	0	0.182
10	0	0.182	0	0.091	-2	0
11	0	0.182	2	0.182	0	0.182
12	0	0.182	-2	0	0	0.182
13	2	0.364	0	0.091	0	0.182
14	0	0.182	0	0.091	0	0.182
15	0	0.182	0	0.091	0	0.182
16	0	0.182	0	0.091	0	0.182
17	1	0.273	-1	0.0455	1	0.273
18	-1	0.091	1	0.1365	1	0.273
19	-1	0.091	-1	0.0455	-1	0.091
20	1	0.273	1	0.1365	-1	0.091

matrix. The mixture is then manually layered into a gear-shaped mold. Each layer is carefully pressed to ensure uniform distribution and eliminate air bubbles. The composite is cured at a controlled temperature of 100°C for 24 hours to achieve optimal mechanical properties. After curing, the gear is removed from the mold and subjected to post-processing to ensure precise dimensions and surface finish as shown in Fig. 1.

Table 2 presents the 20 combinations of specimens based on CCD of RSM. Coded values and actual weight in gm are presented in the table 2. These 20 samples are prepared for tensile test.

The density, yield stress, Young's modulus (Modulus of elasticity) and ultimate tensile stress are recorded for all the specimens and presented in Table 3.

The stress-strain curve (Fig 2.) shows that the material experiences a steady increase in stress with strain until it reaches a maximum stress (24.66 N/mm²) at 5-6% strain. After this point, the material quickly fails, suggesting a brittle nature with limited deformation. The sharp drop, after the peak, indicates the material cannot handle further strain once the maximum stress is exceeded.

This stress-strain curve (Fig 3.) shows the material reaching a peak stress (24.5 N/mm²) at approximately 2% strain, followed by a slight decline and a secondary peak. The material appears to maintain some stress capacity before a sharp failure around 4% strain. The steep drop in stress after the second peak indicates brittle behavior with minimal ductility, as the material fractures soon after reaching its maximum stress.

Table 3 Materials properties

Sample Number	Yield stress (MPa)	Ultimate tensile stress (MPa)	Young's modulus (MPa)	Density (kg/m^{-3})
1	12.0176	19.5839	2164.4	1152.7000
2	10.198	27.7748	2040.4	1188.1100
3	10.0088	24.8776	2001.9	1200.2900
4	10.4064	29.4762	2407.5	1188.1100
5	10.5743	24.0124	2115.3	1126.3600
6	11.2721	22.8953	2029.1	1172.9700
7	10.198	27.7748	2040.4	1182.7600
8	10.7796	19.5	2155.5	1137.3000
9	10.2543	20.5	2050.9	1127.9200
10	11.1595	24.6311	2009.8	1129.0300
11	14.9264	20.7724	2239.0	1150.5900
12	12.5898	24.0195	2266.6	1160.3000
13	11.5866	26.2672	2317.4	1197.7500
14	10.4064	29.4762	2082.1	1129.7500
15	11.4243	29.4762	2285.7	1144.8000
16	12.2565	29.4762	2206.6	1159.5800
17	12.9982	24.5	2601.5	1132.4300
18	12.7335	22.5	2546.8	1160.3800
19	12.6315	26.1367	2526.8	1134.5300
20	12.6431	26.4451	2528.7	1140.9900

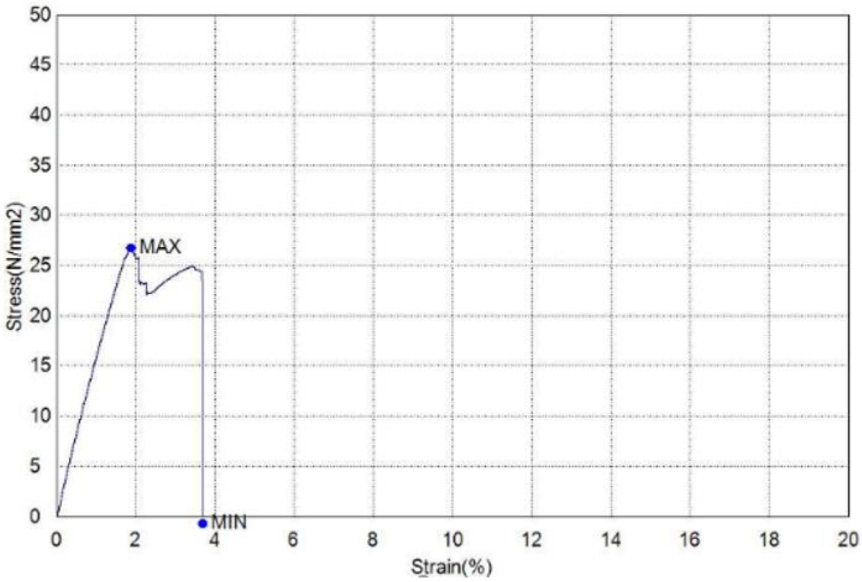

Fig. 3 Stress strain curve for sample 17

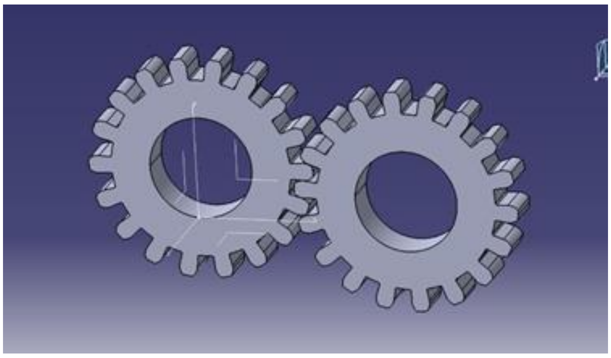

Fig. 4 3D gear model

Table 4 Gear nomenclature

Demension	Unit	Symbol	Value (for both gears in assembly)
Number of Teeth	-	Z	20
Pitch Circle Diameter	mm	D	127
Pressure Angle	degree	ϕ	20
Addendum Radius	mm	RA	69.85
Deddendum Radius	mm	RD	55.88
Face Width	mm	B	25.4
Shaft Radius	mm	RS	31.75

2.2 Modelling of Spur Gear

In this study, maximum contact strength is determined during the transmission of torque using finite element analysis. The spur gear is sketched and modeled in the ANSYS Design Modeler. The dimensions of the gears are given in Table 4. Fig. 4 shows the gear model made using ANSYS.

2.2.1 Theoretical calculation of contact stresses by Hertz equation

Hertz equation is used to determine the contact stresses in the mating teeth of gear. Hertz equation for contact stress in the teeth of mating gears is given by Eq. (1)

$$\sigma_c = \{(F(1 + {}^{r_1}/_{r_2})/(Lr_1\pi[(1-\mu_1^2)/F_1 + (1-\mu_1^2)/F_2]\sin\emptyset)\}\text{^}0.5 \quad (1)$$

where σ_C, F, r_1, r_2, L, Ø, μ_1 and μ_2, F_1 and F_2 are the contact stress in mating teeth of spur gear, force, pitch radii, face width, pressure angle, Poisson ratios, modulus of elasticity of two gears in mesh respectively.

In this paper, finite element analysis is carried out using ANSYS 16.0 Workbench to determine the maximum contact strength for gears modelled using coir fiber/CNT/Fly ash reinforced polymer matrix composite materials. Solid 186 element is used in the discretization process. Convergence study for mesh size is carried out to get the refined results of contact stress.

Fig. 5 illustrates the boundary condition of the mating gears. All degrees of freedom are fixed along the inner rim of the lower gear. Frictionless support is applied on the inner rim of upper gear

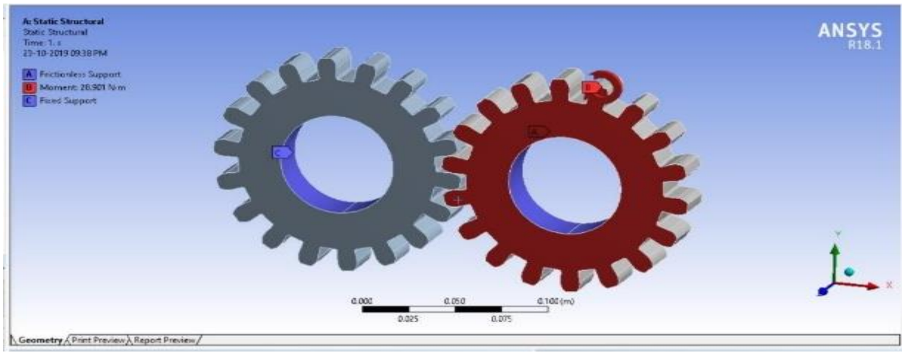

Fig. 5 Boundary condition of gear

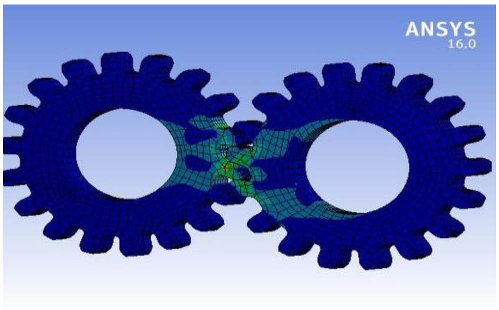

Fig. 6 Equivalent Stress of 8.7229MPa

Table 5 Theoretically Calculated values

Number of Samples	Stress values (MPa) (Numerical)	Stress Values (MPa) (Theoretical)	% Error
1 (Sample 1)	10.0290	9.6000	4.2775%
2(Sample 11)	9.6645	9.6000	0.6673%
3(Sample 12)	8.7229	9.0000	3.07%

to allow its tangential rotation but restrict radial translation. Moment is applied on the inner rim of upper gear in clockwise direction as a driving torque.

3. Results and discussion

Structural analysis is performed for three different compositions such as sample numbers 1, 11 and 12 and the same is validated with hertz empirical model. Table 5 shows the percentage of error between present numerical model and Hertz empirical model. Error is less than 5% which shows the genuineness of the present numerical model.

Fig. 6 shows the stress distribution in the gears. Since the genuineness of the present numerical model based on finite element analysis is validated, further analysis of 20 samples mentioned in Tables 2 and 3 is carried out using finite element analysis. Table 6 presents the stress values for 20 samples based on response surface methodology, a design of experiment tool. Analysis of variance (ANOVA) is employed to find the influences of wt.% of coir, CNT and Fly ash on stress

Table 6 Stress values for 20 samples

No. of samples	Stress values (Analytical)MPa
1	10.0290
2	7.1883
3	7.2357
4	7.1883
5	7.8182
6	7.5589
7	7.1883
8	7.3066
9	7.2941
10	7.3901
11	9.6645
12	8.7229
13	7.3412
14	7.1883
15	7.1883
16	7.1883
17	7.9462
18	7.6412
19	7.3656
20	8.0950

distribution and Fly ash on stress distribution in the gears using DESIGN EXPERT software.

Table 7 gives the ANOVA analysis for maximum strength developed in the gears. The Model F- value of 29.63 implies the model is significant. There is only a 0.01% chance that an F-value greater than this could occur due to noise.

P-values less than 0.05 indicate model terms are significant. In this case B, AB, AC, BC, B^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve the model.

Table 8 gives fit statistics. The values of R^2 and adjusted $R^2$are greater than 0.9 which again shows the significance of the model. Adequate Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. The obtained ratio of 18.294 indicates the adequacy of the signal. This model can be used to navigate the design space. Eq. (2) represents the regression model obtained from the Analysis of variance (ANOVA) analysis.

$$\begin{aligned} &Equivalent\ stress \\ &= 8.28443 - 2.85987 * (Coconut\ fiber) - 21.80870 * (CNT) \\ &+ 0.998950 * (Fly\ ash) - 60.81391 * (coconut\ fiber) * CNT) \\ &+ 39.67214 * (Coconut\ fiber) * (Fly\ ash) \\ &-107.72854\,(CNT) * (Fly\ ash) + 334.96471 * (CNT^\wedge 2) \end{aligned} \tag{2}$$

Table 7 ANOVA for equivalent stress

Source	Sum of Squares	DOF	Mean Square	F-value	p-value	
Model	12.30	7	1.76	29.63	< 0.0001	Significant
A-Coconut fiber	0.1478	1	0.1478	2.49	0.1404	
B-CNT	1.88	1	1.88	31.62	0.0001	
C-Fly ash	0.2647	1	0.2647	4.46	0.0562	
AB	0.5072	1	0.5072	8.55	0.0127	
AC	0.8634	1	0.8634	14.56	0.0025	
BC	1.59	1	1.59	26.84	0.0002	
B^2	7.05	1	7.05	118.89	< 0.0001	
Residual	0.7116	12	0.0593			
Lack of Fit	0.7116	7	0.1017			
Pure Error	0.0000	5	0.0000			
Cor Total	13.01	19				

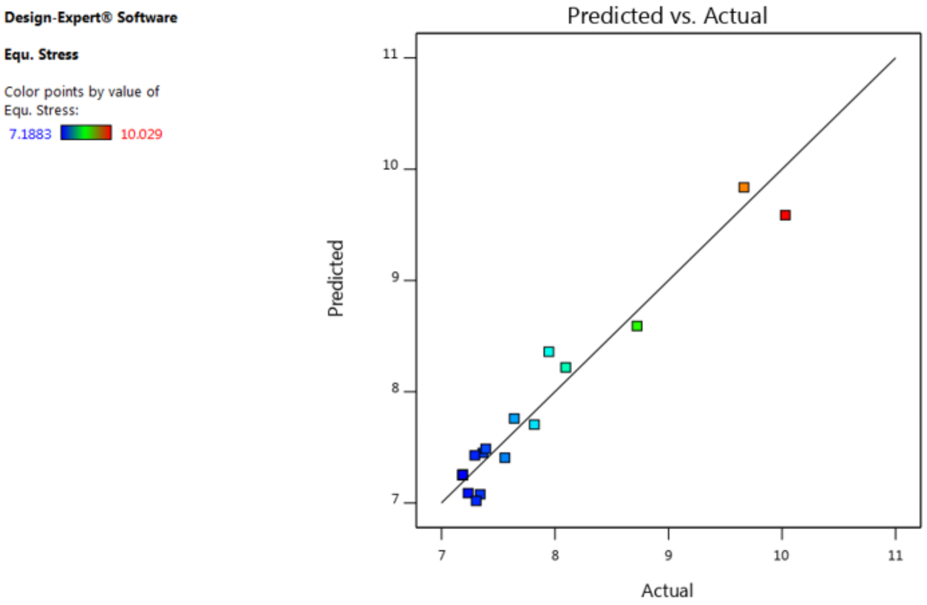

Fig. 7 Comparison of Predicted Vs Actual Values

The Eq. (2) can be used to make predictions about the response for given levels of each factor. Here, the levels should be specified in the original units for each factor. This equation should not be used to determine the relative impact of each factor because the coefficients are scaled to accommodate the units of each factor and the intercept is not at the center of the design space Fig. 5 explains the comparison of predicted and actual values.

Table 9 compares the results obtained from FEA and regression equation. From the table it is evident that the error between FEA and regression equation is less than 5% which shows the strength of regression equation.

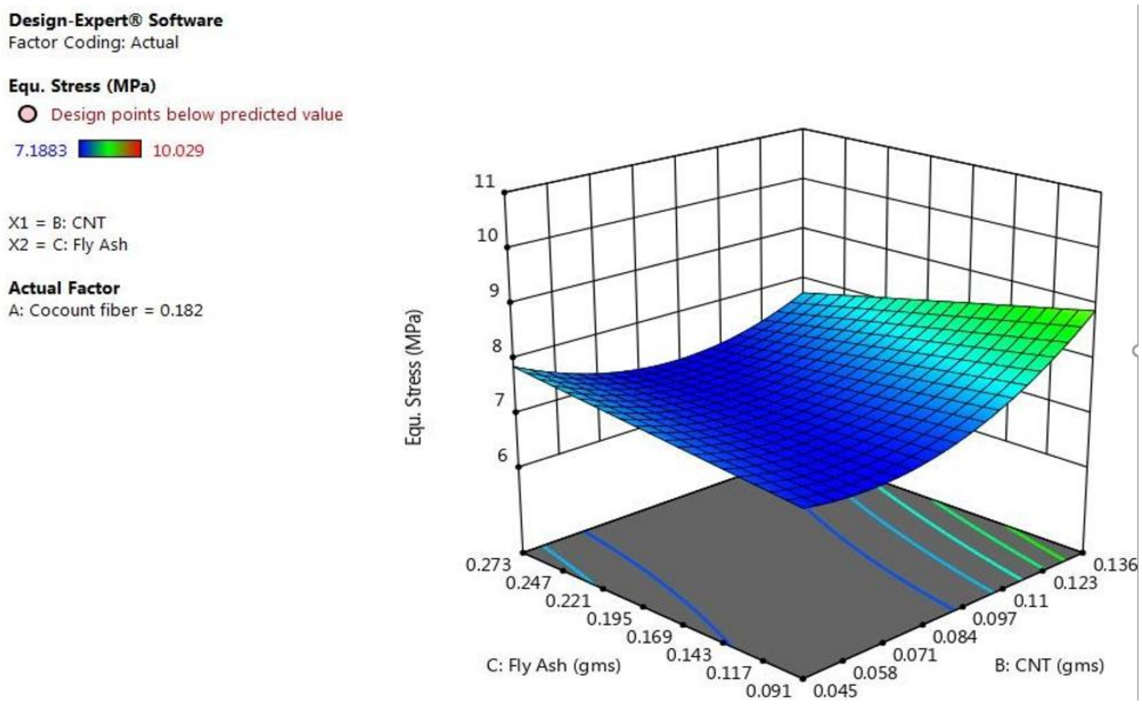

Fig. 8 Response surface plot showing the effect of CNT, Fly ash on maximum strength at 0.182gms of coconut fiber

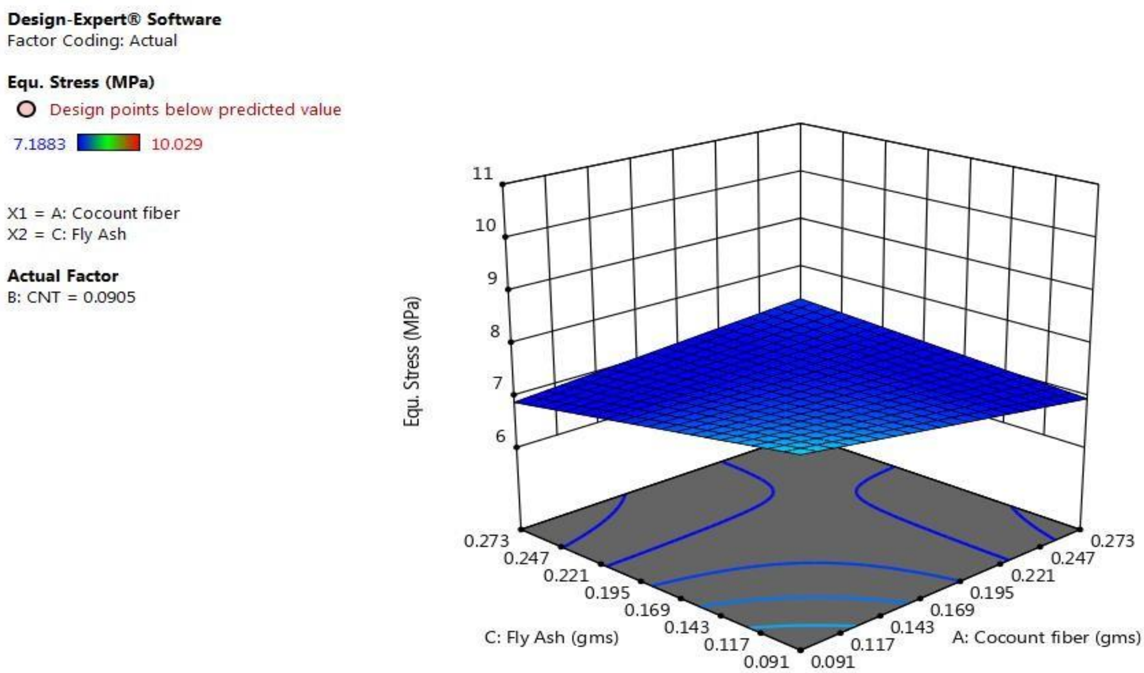

Fig. 9 Response surface plot showing the effect of Coconut fiber, Fly ash on maximum strength at 0.0905gms of CNT

Table 8 Fit Statistics

Standard Deviation	0.2435	R^2	0.9453
Mean	7.73	Adjusted R^2	0.9134
Coefficient of Variation (%)	3.15	Predicted R^2	0.6596
		Adequate Precision	18.2937

Table 9 Comparison of FEA results Vs Regression equation results

No. of samples	Actual value (MPa)	Predicted value (MPa)	Error%
1	7.64	7.76	-1.57
2	8.10	8.22	-1.48
3	7.82	7.71	1.406
4	7.29	7.43	-1.92
5	10.03	9.59	4.38
6	8.72	8.59	1.49
7	7.34	7.08	3.54
8	7.56	7.41	1.98
9	7.19	7.25	-0.834
10	7.37	7.45	-1.085
11	7.19	7.25	-0.834
12	7.31	7.02	3.96
13	7.24	7.09	2.07
14	7.19	7.25	-0.834
15	7.19	7.25	-0.834
16	9.66	9.84	-1.863
17	7.19	7.25	-0.834
18	7.19	7.25	-0.834

Fig. 8 shows the Response surface plot showing the effect of CNT, Fly ash on equivalent stress. From the graph, the maximum equivalent strength obtained is 8.9MPa at Fly ash 0.091% w/w ratio and CNT at 0.136%w/w ratio.

Fig. 9 shows the Response surface plot showing the effect of Coconut fiber, Fly ash on equivalent stress. From the graph, the maximum equivalent strength is 7.3MPa which is obtained at Fly ash of 0.091 %w/w ratio and coconut Fiber of 0.091 %w/w.

Fig. 8 shows the response surface plot effect of Coconut fiber and CNT on stress by keeping Fly ash as constant at 0.182 w/w ratios. From the graph, the equivalent stress 8.5MPa is obtained at CNT of 0.136 %w/w ratio and Coconut fiber of 0.091% w/w ratio.

3.1 Optimisation and verification of model

Derringer's desirability function optimization methodology is employed to get optimum condition to achieve maximum equivalent strength. 'Maximum level' and 'high importance' for equivalent stress are fed into the software and the optimized condition is obtained. Fig. 11 shows

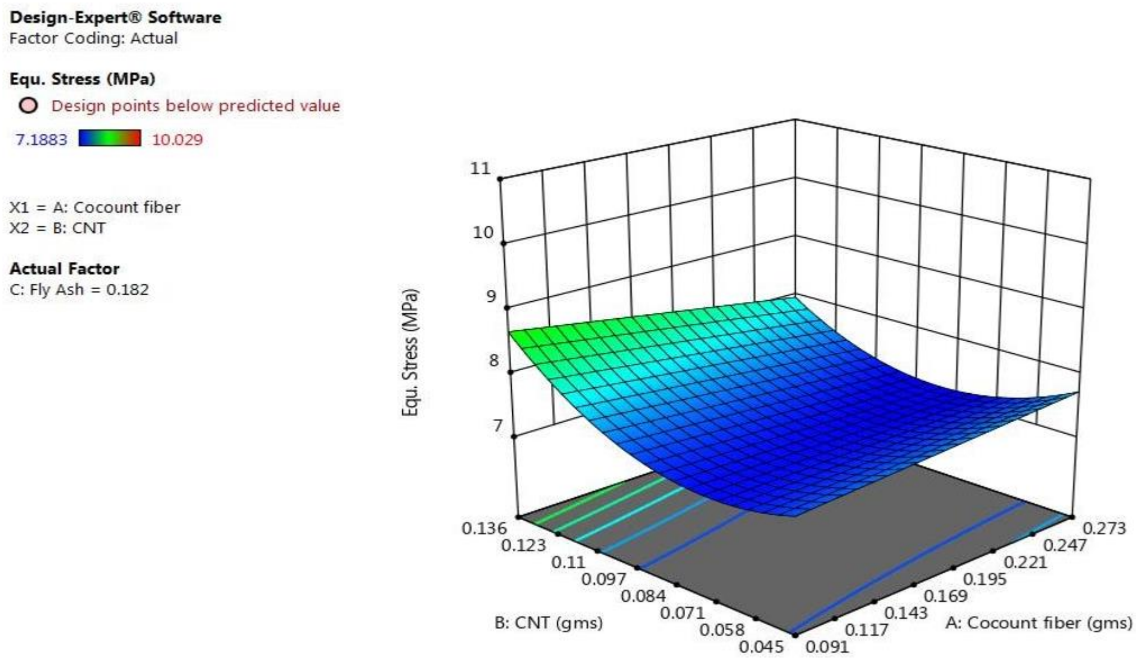

Fig. 10 Response surface plot showing the effect of Coconut fiber, CNT on maximum strength at 0.182gms Fly ash

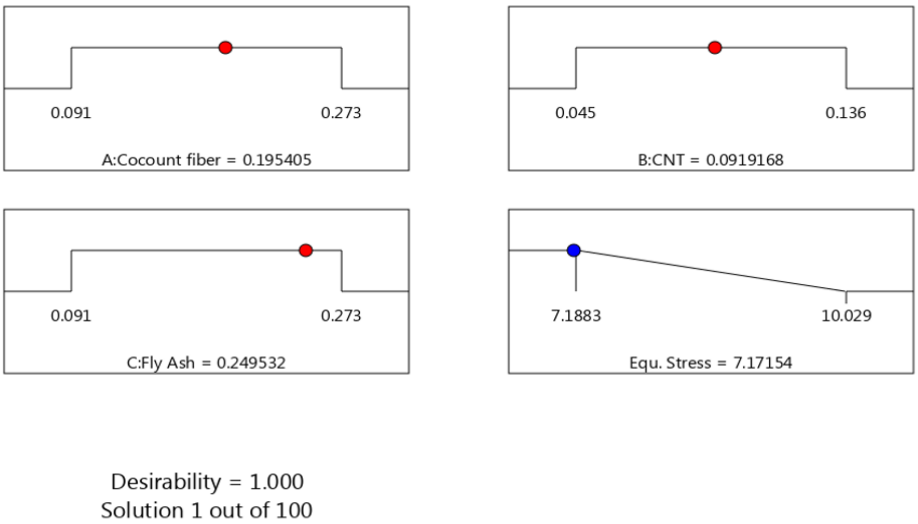

Fig. 11 Desirability ramp for optimisation

the desirability ramp for optimizing the input variables to obtain the maximum outcome. From Fig. 11, it is recommended to set the input variables of coconut fibers at 0.194%w/w ratio, CNT at 0.092%w/w ratio and Fly ash at 0.25% w/w ratio to obtain the maximum outcome of equivalent strength at 7.17MPa. Table 10 shows the constraints of the combinations used.

Table 10 Shows the constraints

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A: Cocount fiber	is in range	0.091	0.273	1	1	3
B: CNT	is in range	0.045	0.136	1	1	3
C: Fly ash	is in range	0.091	0.273	1	1	3
Equivalent. Stress	minimize	7.1883	10.029	1	1	5

4. Conclusions

In this work, an attempt is made to analyze the Involute Spur Gear made from Natural fiber reinforced Polymer Matrix Composites with epoxy resin as matrix and twenty different Composition of CNT, Coconut fiber and Fly ash as reinforcement material.

- It is observed that sample number 1 and 11 has maximum and minimum contact strengths and remaining samples contact stresses are in between them as shown in the table 5 and the contact stress are below its yield stress values of individual sample composition of composite material.
- The obtained contact stresses of all samples are compared with hertz theory and it shows less than 10% of error between FEA results and Hertz results.
- The regression equation is developed with the help of Design Expert software and values predicted from regression analysis are in good agreement with FEA results.
- It is concluded that this type of involute spur gear made from natural fiber reinforced composites can be used in low speed and low strength applications.

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