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Mechanical Properties and Stress Analysis of Natural Fiber Reinforced Polymer Composite Spur Gear

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Abstract. This research study investigates the mechanical properties of polymer composites reinforced with natural fibers, specifically Palmyra palm leaf stalk fiber (PPLSF) and Palmyra palm primary leaf stalk fiber (PPFLSF). Tensile, flexural, and impact strength were among the composites' mechanical parameters generated by integrating these fibers into a polymer matrix and assessing them experimentally. Additionally, stress analysis of a spur gear was conducted using the finite element analysis software ABAQUS. The composite material properties obtained from the experimental investigation were used in the analysis to evaluate the gear's stress distribution and deformation behavior. The bending stress at the pitch point of the natural composite gears for PPLSF, PPFLSF, and nylon synthetic material is analyzed using analytical and experimental methods by ABAQUS software. Finally, the results are compared with each other. The results show that stress induced by nylon is comparatively higher than that of PPLSF and PPFLSF fiber. By analyzing these composites' strength, durability, and stress distribution under operating environments, the study aims to determine whether they are suitable substitutes for conventional materials.

Keywords: composite material, natural fiber, nylon, finite element analysis, von Mises equivalent stress.

1 Introduction

According to several studies, natural fibers, including banana, elephant grass, sisal, jute, vakka, bamboo, Roystonea regia, and coconut, are reinforced in composite materials. Various sectors, including the automotive, marine, sports goods, and structural ones, use other natural fibers such as kenaf, hemp, flax, ramie, bamboo, coir, bagasse, and sugarcane [1, 2].

Despite the growing interest in natural fiber composites, there is limited knowledge and research specifically addressing their use in spur gears. Critical areas for further exploration include material selection and characterization, development of manufacturing techniques, structural integrity and performance evaluation under varying conditions, understanding tribological properties, comparative studies with conventional metal gears, and application-specific research. Addressing these research gaps will contribute to a deeper understanding of the potential of natural fiber composites in spur gear applications, guiding their design and optimization for improved performance and reliability [3, 4].

2 Literature Review

Maurya et al. [5] examined the influence of alkali treatment on surface modification that enhanced adhesion between the fiber and polymeric resin, making Palmyra palm primary leaf stalk fiber (PPFLSF) a better natural fiber composite.

Mahalingam et al. [6] studied the properties of raw and alkali-treated Palmyra palm leaf stalk fiber (PPLSF) and concluded that alkali treatment removes impurities that help better bonding and improve physical and chemical strength.

Qu et al. [7] reviewed natural fiber-reinforced polymer composites and concluded that they exhibit beneficial properties whose mechanical behavior provides the advantage to be used in commercial applications and further its properties can be enhanced by introducing chemical treatments and analysis of bending stress in gear, made of composite material that favors the replacement of plastic gears [8].

Plastic gears exhibit weak mechanical properties and heat conduction that aids in decreased strength and poor performance [9]. The weight reduction of mechanical parts is a critical prerequisite for minimal energy utilization and fulfilling environmental guidelines. In reaction to these global trends, composite materials have been considered for different applications [10].

3D printing is a productive manufacturing technique, and the gears used there require noiseless performance. Also modeled stainless steel spur gear and subjects to contact and bending stress analysis by theoretical equation and finite element analysis (FEA) in ANSYS software that resulted in maximum equivalent stress of 4.2 MPa and total deformation of 0.7 μm and inferred that for a given torque specification, the maximum stress and total deformation can be calculated.

Bharti et al. [11] analyzed and compared the contact stress of spur gear made from Silicon Nitride and conventional steel using the von Mises stress formula and FEA and concluded that the spur gear made from silicon nitride shows better comparative stress and reduced strain and strain energy that strengthens its life.

Ahmed et al. [12] studied various types of failures in unreinforced and carbon-reinforced Nylon 66 spur gears and concluded that the reinforced gears have a better life in comparison with the unreinforced gears as they possess high mechanical properties [13].

Engineers hold composites with greater esteem after investigating gear components made of polymer composites with natural fibers. In this investigation, the coconut tree sheath stiffens the epoxy matrix. The coir sheaths made of coconuts are readily accessible, lightweight, and inexpensive. Alkali treatment improves the mechanical characteristics of coir hybrid composites. Glass short fiber and coir fiber were used in increments of 20, 30, and 40 % to stiffen the composites.

Rama Thirumurugan et al. [14] have examined hybrid composites' impact and bending strengths. Coir gear tooth's bending strength was also investigated in FEA research [15]. Simultaneously, there has been a noticeable change in the use of plastic gears and their replacement with natural fiber alternatives [16]. Environmental concerns and a desire for biodegradable materials are driving this change. As processing techniques and material science continue to advance, natural fiber gears will be essential in creating a future where engineering is more sustainable and mindful of the environment [17].

The literature review confirmed that significant attempts were only made to analyze spur gears made of natural fiber composite material to replace nylon gear. Also, the bending stress calculated by theoretical, FEA, and experimentally for PPLSF, PPFLSF, and nylon gear is analyzed in this paper.

3 Research Methodology

3.1 Materials

The Palmyra tree was used to extract PPLSF and PPFLSF, and the milling machine was utilized to mill the fibers to create the composite materials. The PPLSF and PPFLSF reinforced composite materials plate is produced using the compression molding technique. The tensile, bending, and impact strength specimens were cut and tested from the plate.

The PPLSF and PPFLSF milled composite material showed in is shown in Figure 1.

a

b

Figure 1 – PPLSF (a) and PPFLSF (b) composites

The considered materials include nylon-6 composites, PPLSF, and PPFLSF. After using an optimized weight ratio of 30:70, the properties of alkali-treated Palmyra palm leaf stalk fiber composite (APPLSFC), alkali-treated Palmyra palm primary flower leaf stalk fiber composite (APPFLSFC), and nylon-6 are examined. APPLSFC and APPFLSFC are reinforced with polyester by compression molding technique and are treated with 5 % alkali.

The alkali treatment of the fibers prompted fiber fibrillation, changed crystallinity, and improved the material properties, resulting in higher strength and good bonding between matrix and fiber. Nylon-6 is a thermoplastic material and one of the widely used materials in gear production for small applications.

For alkali treatment, the fibers were submerged separately in a 5 % sodium hydroxide solution for thirty minutes. Continuous washing with water was utilized to remove the alkali moieties from the fibers. After the fibers had been cleaned once more with hydrochloric acid

(HCl) at a concentration of 3 % wt., which was used to remove extra molecules from the fibers' surface, they were then cleaned with distilled water and let dry for two days at room temperature [18].

For static mechanical testing, the tensile properties of the composites were determined using an Instron tensile tester. The tensile characteristics of the composites were assessed at a crosshead speed of 5 mm/min using the standard ASTM: D 638 "Tensile Properties of Plastics". The specimens' flexural strength was tested using a Kalpak Universal Testing Machine in compliance with the standard ASTM D790-03 "3-Point Flexure Test on Plastics", which has a 20 kN capacity and a crosshead speed of 2 mm/min. In this instance, composite specimens were cut out for the impact test in compliance with ASTM: D256. Three samples were examined for every test, and the average outcomes were noted (Figure 2).

a

b

c

Figure 2 Specimens for determining mechanical properties:
a – APPLSFC; b – APPFLSFC; c – nylon-6

3.2 Analysis of mechanical properties

The PPLSF composite has a maximum tensile strength of 34.22 MPa and a tensile modulus of 1.83 GPa. The highest values for the composite of PPLSF are 56.03 MPa for flexural strength and 2.47 GPa for flexural modulus. The 9.36 kJ/m^2 is the most significant impact strength recorded for composite PPLSF. Interlayer forces control the mechanical strength of powder-reinforced polyester matrix composites because loads are applied vertically along the transverse axis of the composite.

The composite's highest mechanical characteristics demonstrate a solid bond between the fiber and matrix (Table 1).

Table 1 – Mechanical characteristics of fiber composites made of PPLSF and PPFLSF with various natural fiber composites

Composite	Tensile strength, MPa	Tensile modulus, GPa	Flexural strength, MPa	Flexural modulus, GPa	Impact strength, kJ/m^2
PPLSF	34.22	1.83	56.03	2.47	9.36
PPFLSF	32.53	1.56	51.03	1.47	8.29
Hemp	34.64	2.56	60.51	3.41	7.35
Kenaf	32.14	2.48	57.35	2.99	3.24
Banana	17.68	1.02	33.51	1.59	9.36
Jute	34.77	1.89	66.26	3.68	8.65
Straw	32.67	1.62	47.10	2.17	2.65
Sisal	28.55	1.49	53.42	4.25	9.61
Coir	18.61	1.16	31.15	1.50	3.91

The composites' thermal stability was assessed using thermo-gravimetric analysis (TGA) in compliance with the standard ASTM E1131 "Standard Test Method for Compositional Analysis by Thermogravimetry".

During TGA, the samples were put through a temperature-controlled program while a thermo-gravimetric analyzer [19] continuously monitored the changes in theirously.

3.3 Gear Modelling

The spur gear is designed in SolidWorks and analyzed in ABAQUS software, which is more intuitive and offers accurate results. A spur gear is designed in SolidWorks with parameters listed in Table 2 and verified against the existing theoretical formula.

Table 2 – Design parameters of spur gear

No.	Parameter	Value
1	Pitch circle diameter, mm	40
2	Module, mm	2.0
3	No of teeth	20
4	Pressure angle α, °	20
5	Addendum, mm	2.0
6	Dedendum, mm	2.5
7	Whole depth, mm	4.5
8	Outside/tip diameter, mm	45
9	Tooth thickness, mm	3.5
10	Face width, mm	12

The designed gear model is then imported into Abaqus CAE software. Firstly, the material is defined by inputting the material properties into the software. First, the top and bottom blanks were cleaned, and the blank cavity was covered with a mold release agent, making removing the composite blank from the die much more straightforward. Next, the short fibers were randomly arranged in the bottom die, and the matrix was made by mixing unsaturated polyester resin, accelerator, and catalyst. The die was then sealed with a top plate, and the matrix was compressed for 12 hours at room temperature after removing the composite gear blank from the die. The composite gear was carved from a composite gear blank using a gear hobbing machine.

The part was then meshed (Figure 3), creating an instance and a step to apply the load.

Figure 3 – PPLSF composite gear

Solid elements: These elements are used for analyzing solid structures and are well-suited for stress and strain analyses [16]. Examples include C3D8 (8-node linear brick), C3D20 (20-node quadratic brick), and C3D8R (8-node reduced integration brick). This work uses C3D8 (8-node linear brick) for analysis [20, 21].

During experimental designing, the part's boundary condition is then defined by keeping the central hole fixed, followed by applying load on the pitch point (Figure 4).

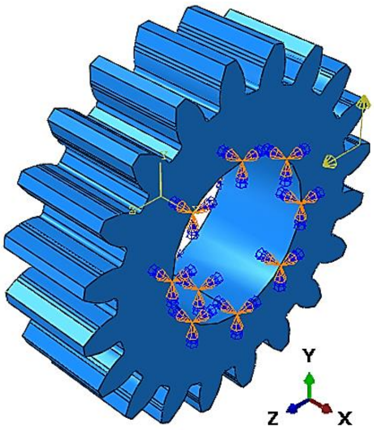


Figure 4 – Boundary conditions and applied loads

Tangential and radial loads are calculated using the following equations:

$$W_t = \frac{2T}{D_p}; \tag{1}$$

$$W_r = W_t \sin(\alpha), \tag{2}$$

where W_t, W_r – tangential and radial loads, respectively, N; T – torque, N·m; D_p – pitch diameter, m; α = 20° – pressure direction angle.

The Lewis equation evaluates the theoretical bending stress σ_b, MPa:

$$\sigma_b = \frac{W_t}{fmY}, \tag{3}$$

where f – face width, mm; m – module, mm; Y – Lewis form factor.

Tangential and radial loads are given at the pitch point of the gear. Then, a job is created for each work, and the model is simulated. The results are saved as an open database (ODB).

The universal testing machine (UTM) is used to apply the load on the gear to study the static gear tooth deflection test rig. At first, the test rig is placed on the compression plate on the UTM. Then, the middle crosshead is moved downwards and placed on the test rig's load shaft.

The value of the LED display is reset to zero at the starting point, and the load is applied gradually on the steel gear with the load shaft's help, as shown in Figure 5.

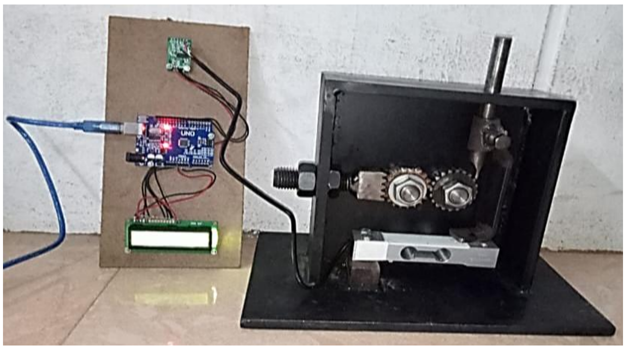


Figure 5 – Static gear tooth deflection test rig

The load is transmitted to the composite gear, and its deflection and breaking point is noted on the LED display using a load shell sensor.

4 Results

4.1 Thermogravimetric analysis

This composite was subjected to a single-stage thermal degradation process that ranged from 30 °C to 600 °C, as shown in Figure 6.

The whole composite also showed a regular breakdown pattern in this test.

The residual mass decomposed more quickly over the four phases of decomposition at lower temperatures. Between 180 °C and 210 °C, the composites proceeded through the first phase of disintegration. The solvent has been removed, and the moisture in the composite has evaporated. The 2nd stage of composite deterioration occurred at temperatures ranging from 280 °C to 300 °C.

Decomposing substances, such as lipids and waxes, were removed in this region through an alkaline treatment with 17 % and 16 % residual mass, respectively, provided by the PPFLSFC and PPLSFC.

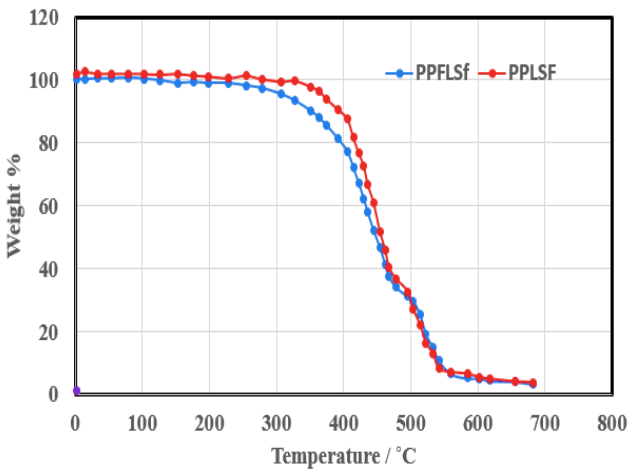


Figure 6– TGA of PPLSF and PPFLSF composites

Between 360 °C and 420 C, the composite underwent its third stage of degradation. Volatilization of the composite and the soft section were also impacted, along with the degradation of lignin, hemicelluloses, and cellulose.

The composites’ last stage of disintegration occurs between 490–514 °C.

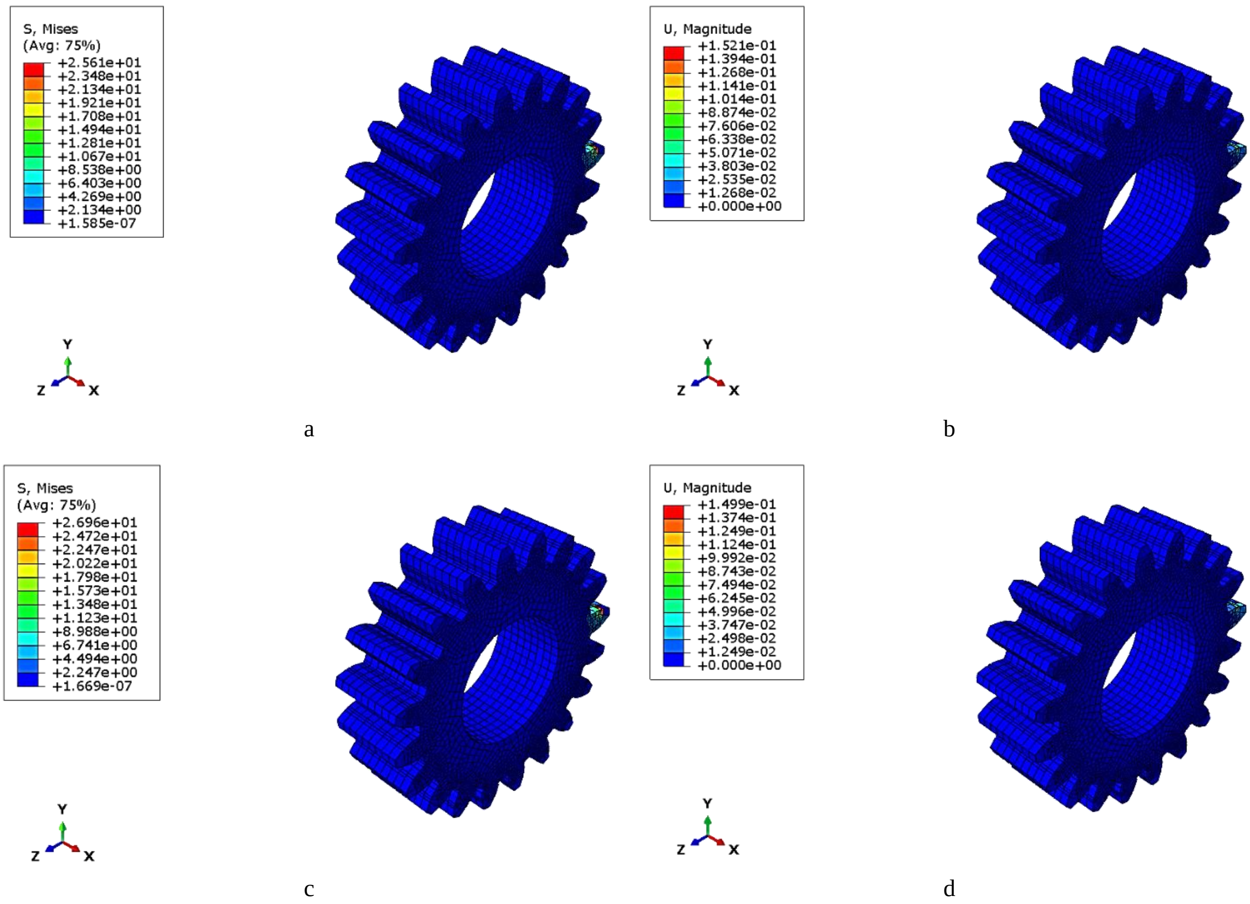
4.2 Stress analysis of composite gear

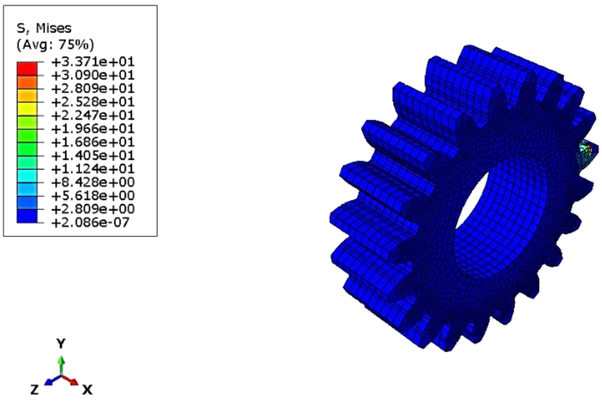
The results reflect the bending stress and gear deformation at the pitch point. The simulated results and the theoretical values were then assessed and found to be within the limits. Stress is the ratio of the force applied to the area.

Table 3 compares deflection and bending stress on composite spur gear [22, 23]. Figure 7 depicts stresses and deformations for PPLSF, PPFLSF, and nylon-6.

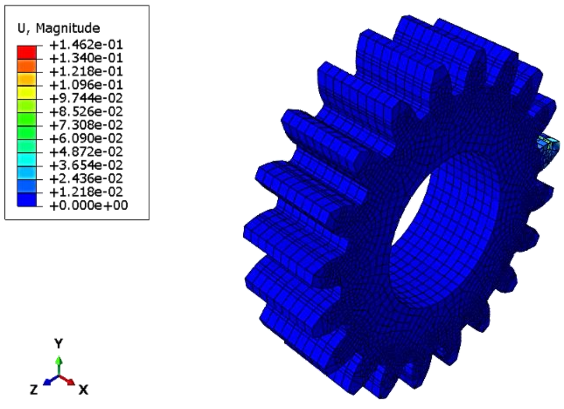
Table 3 – Comparison of deflection and bending stress on the composite spur gear

Composite	Load, N	Deflection, mm	Bending stress, MPa	Deflection, mm	Bending stress, MPa
		Gear test rig	Lewi’s equation	FEA	
Nylon gear	550	0.099	34.7	0.146	33.7
PPLSF composite gear	440	0.106	27.8	0.149	27.0
PPFLSF composite gear	390	0.113	26.4	0.152	25.6





e



f

Figure 7 – PPLSF composite gear stress: a, b – PPLSF composite gear; c, d – PPFLSF composite gear; e, f – nylon-6 gear; a, c, e – stress, MPa; b, d, f – deformations

It can be observed that stress-induced for PPLSF and PPFLSF fiber composites are comparatively lower than that of nylon composites.

5 Discussion

The torque exerted from the driver gear is applied to the driven gear teeth at the pitch point, which develops stress where contact is made. When the stress at the contact point exceeds the safe limit, the crack propagation decreases the gear's lifetime and impacts the efficiency and performance. Errors in the simulation are negligible.

The root bending stress at the pitch point calculated theoretically based on Lewi's equation for PPLSF and PPFLSF and nylon gears are 27.78, 26.39, and 34.72 MPa, respectively.

On the contrary, the root bending stress obtained from finite element analysis based on von Mises theory for PPLSF and PPFLSF and nylon gears are 26.96, 25.61, and 33.71 MPa, respectively. Similarly, the deformation for PPFLSF, PPLSF, and nylon gears are 0.152, 0.149, and 0.146 mm, respectively.

The deformation is inversely proportional to stress such that it is relatively high for PPLSF, which has lower stress, and lower for nylon, which possesses higher bending stress.

Figure 7 illustrates that the stress of natural fiber composites is comparatively lower than that of nylon gear. Analyzing the results of root bending stress, Lewi's equation and FEA stress are approximately equal, suggesting that Lewi's equation can be used for quick calculation.

ABAQUS software has given outcomes very close to the theoretical values, affirming its integrated program and the ease of analyzing complex meshes.

Because of the poor heat coefficients in nylon gear, the higher stress developed in the contact area affects the mesh length of single teeth and results in vibration, noise, and transmission errors and crippling its performance and could also lead to surface pitting.

Improving natural fiber composites' properties by infusing enhanced reinforcements and surface modification by coating makes it possible to make the material the best substitute for plastic gears.

6 Conclusions

The experimental investigation of PPLSF and PPFLSF reinforced polymer composites revealed significant enhancements in mechanical properties compared to the pure polymer matrix. The stress analysis of the spur gear using ABAQUS provided valuable insights into its stress distribution and deformation behavior. These results enhance our knowledge of the possibilities of natural fiber composites in gear applications and present chances for optimizing them for increased dependability and performance. It can be inferred that the bending stresses (26.39 MPa and 27.78 MPa, respectively) for natural fiber composites such as PPLSF and PPFLSF were comparably lesser than the nylon gear (34.7 MPa) [24].

Contrarily, the deformation for natural fiber composites was relatively more significant than that of nylon gear. The stress induced for natural fiber composites was nearly as much as the nylon gear. Although the stress values were higher for nylon, the deviation was within limits and negligible. Furthermore, the stress analysis of a spur gear using ABAQUS provided valuable insights into the stress distribution and deformation behavior.

Incorporation of the composite material properties obtained from the experimental investigation, allowed for a more accurate assessment of the gear's performance under different operating conditions.

These findings expand our understanding of the potential of natural fiber composites and provide insight into optimizing them for improved performance and longevity in gear applications.

Testing will be conducted under a variety of load conditions and heat conditions on these composite gears so that they may be used in various potential applications.

If stress analysis and experimental assessments of mechanical properties are combined, the behavior of PPLSF and PPFLSF reinforced polymer composites in gear applications could be better understood. Thanks to this study, more sustainable and lightweight solutions in various industries may be realized, which lays the framework for future investigations into gears composed of natural fiber reinforced polymer composites.

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