

Tensile Strength Evaluation of Natural Fiber Laminates Using Taguchi Method and FEA Validation

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ABSTRACT

This research reports the integrated experimental-statistical-numerical study on tensile behaviour of natural fibre epoxy composite laminates reinforced with sisal, jute and hybrid combination of sisal and jute. Laminates were made with controlled fiber orientations (0-45deg, 0-90deg and 45-90deg) and tested under tensile loading as per ASTM D638-2014. The experimental results showed that the tensile strength varies significantly for different types of fiber and direction, and laminates made of sisal fibers show better performance than jute and hybrid systems. To maximize and predict tensile strength, the Taguchi method was used, and the results of the regression-ANOVA analysis have been found to be good model fitting with R2 of about 0.93 and high statistical significance. Finite Element Analysis (FEA) with the help of ANSYS 2024R1 was performed to validate the experimental results, which showed the maximum equivalent stress of 26.675 MPa, maximum shear stress of 13.349 MPa, and maximum deformation at the midpoint of the specimens. The numerical trends were very similar to experimental behaviour, with small deviations explained by idealized simulation conditions. The results show that fiber orientation is a dominant factor in the tensile performance and that hybrid laminates need to be further optimized with a consistent strength improvement. The study establishes and proves that the combination of experimental testing, Taguchi optimization, and FEA validation is a framework that can be used to reliably design and develop sustainable natural fiber composite materials.

Keywords- *Finite Element Analysis, Hybrid Laminates, Natural Fiber Composites, Taguchi Method, Tensile Strength.*

1. INTRODUCTION

Research on the evaluation of tensile strength of sisal, jute and hybrid natural fiber epoxy laminates has become a critical area of research due to the demand of sustainable composite materials for automotive, construction and lightweight engineering applications [1], [2]. During the past decade, natural fiber reinforced composites have received great attention due to their biodegradability, renewability and good mechanical properties compared with synthetic fibers [3], [4]. The evolution of this field has witnessed the progress from the elementary and experimental characterizations to the sophisticated optimization and numerical validation methods like the Taguchi method and finite element analysis (FEA) leading to the improvement of predictive accuracy and the optimization of the performance of such composites [5], [6]. The world market for natural fiber composites is expected to expand significantly by their practical importance in the mitigation of environmental impact and the enhancement of fuel efficiency in the transportation industries [7].

Despite these advances, challenges still exist in the accurate prediction and optimization of the tensile strength of natural fiber composites, especially the laminates that are a hybrid of sisal and jute fibers [8], [9]. Existing studies have commonly found variability in mechanical performance attributed to issues with fiber-matrix adhesion, fiber anisotropy and processing parameters [3], [4], [5]. Moreover, although there are improvements

from hybridization with synthetic fibre and addition of nanofillers, the synergy and the optimal configuration for natural fibre hybrids contains further elucidation [10], [11]. Differing viewpoints can be found about the success of chemical treatments and hybridization approaches, with some research showing strong improvements while others report weak or inconsistent outcomes [12], [13], [14]. The absence of full sets of experimental-statistical-numerical frames restricts the possibilities of the reliable use of these materials in important engineering areas [15], [16].

2. LITERATURE REVIEW

Research concerning optimization and prediction of the tensile strength is attempted with experimentation, Taguchi method and numerical investigation. Applicable to sustainable composite materials for automotive, construction, and lightweight engineering uses.

Table 1 Analysis of Recent Studies

Study	Optimization Techniques	Experimental Validation	Fiber Hybridization Effects	Treatment and Fabrication Parameters	Application Relevance
[1]	Taguchi L27 design with statistical validation for fiber ratios	Strong agreement between FEM and experiments	Hybrid of curauá, jute, sisal optimized at 20/10/5 wt%	Fiber volume fraction up to 35%, hybrid ratios critical	Automotive and aerospace composites
[2]	Mechanical and erosion testing	Fractographic evidence of adhesion	Flax, jute, luffa epoxy composites	Fiber type and adhesion	Sustainable composite applications
[3]	ABAQUS FEA with anisotropic fiber modeling	Numerical and experimental tensile tests	Unidirectional sisal fiber composites	Fiber volume fraction and anisotropy	Comparable strength to aluminum alloys
[5]	Hand layup with E-glass and jute fibers	FEA validation with 4% error	Jute-E-glass hybrid composites	Fiber weight fraction and stacking sequence	Numerical and experimental correlation
[6]	Grey-based Taguchi method for fabrication parameter optimization	Experimental validation of grey relational grade	Sisal fiber composites	Fiber length, content, diameter optimized	Vinyl ester matrix composites
[7]	CAD modeling and FEA with ply orientation and thickness	Tensile and deformation results analyzed	Jute fiber and hybrid laminates	Ply orientation and laminate thickness	UAV wing skin and structural components
[8]	RSM with Box-Behnken design	Experimental confirmation of optimal parameters	Hybrid natural fiber composites	Fiber type, chemical treatment, volume fraction	Epoxy and polyester matrix composites
[9]	Experimental evaluation of hybrid sisal/jute composites	Mechanical testing confirms hybrid benefits	Various weight ratios (100/0 to 0/100) at 20-30% fiber fraction	Hand layup and compression molding techniques	Improved mechanical properties for structural use

Study	Optimization Techniques	Experimental Validation	Fiber Hybridization Effects	Treatment and Fabrication Parameters	Application Relevance
[10]	Hand layup with variable eggshell powder filler	SEM analysis of interfacial adhesion	Sisal-glass hybrid composites with ESP	ESP content and stacking sequence	Eco-friendly composites for automotive and aerospace
[11]	Taguchi S/N ratio and ANN modeling	Neural network predicts mechanical properties	Jute fiber with silica nanoparticles	Silica nanoparticle concentration	Automotive and aircraft industry applications
[12]	Experimental and chemical treatment effect analysis	SEM fracture surface analysis	Jute, sisal, curaua hybrid composites	Alkali and silane treatments	Mechanical property enhancement via hybridization
[13]	Alkali and fungal treatments	Microscopy and water absorption tests	Hemp-sisal fiber composites	Treatment effects on bonding	Automotive interiors and packaging
[14]	Hydrothermal aging and mechanical testing	Numerical modeling with ANSYS	Sisal and glass fiber composites	Aging effects on mechanical properties	Sustainable advanced materials
[15]	Genetic algorithm optimization with FEA modeling	FEA validated with experimental tensile tests	Jute, glass, and hybrid composites	Stacking sequence and fiber orientation	Industrial applications balancing performance and sustainability
[16]	Finite element analysis of fiber volume	Correlation with experimental tensile strength	Sisal fiber epoxy composites	Fiber volumetric fraction	Mechanical property prediction
[17]	Taguchi L27 array optimizing fiber orientation and matrix	Experimental results matched Taguchi predictions at 95% confidence	Jute-basalt hybrid with orientation effect (45° best)	Orientation and matrix type significant	Superior to e-glass and carbon fiber composites
[18]	Taguchi grey relational optimization for multi-property enhancement	Experimental validation of optimized parameters	Hybrid sisal-banana fibers studied	Process parameters optimized via Taguchi	Lightweight engineering applications
[19]	Response surface methodology with FEM for RVE design	FEM validated with literature data	Jute-sisal hybrid at 1:1 ratio	Fiber volume fraction, diameter, length studied	Composite micromechanics and design
[20]	Experimental and FEM modeling with alkaline treatment variations	FEM mesoscale model validated with experiments	Sisal fiber in various textile architectures	Alkaline treatment (6 wt% NaOH) and fiber architecture	Automotive lightweight structural composites

Study	Optimization Techniques	Experimental Validation	Fiber Hybridization Effects	Treatment and Fabrication Parameters	Application Relevance
[21]	Taguchi optimization combined with statistical regression	Experimental and modeling results aligned	Jute/E-glass hybrid with nanoclay filler	Nanoclay filler content and fiber wt% optimized	Enhanced mechanical properties for hybrid composites
[22]	Taguchi L9 design optimizing compression molding parameters	SEM analysis supports mechanical test results	Jute-sisal hybrid composites	Heating temperature, compression pressure, mold temperature	Fabrication process optimization for hybrid composites
[23]	ANOVA and RSM for hybrid flax, jute, sisal composites	Statistical models validated experimentally	Hybrid composites with 80% jute and 20% flax	Volume fraction and chemical treatment effects	Enhanced tensile and flexural properties
[24]	Experimental tensile, flexural, impact tests on hybrid composites	Mechanical tests confirm fiber loading effects	Sorghum bicolor, sisal, jute hybrid with polyester matrix	Fiber weight fraction variation	Automotive and construction applications
[25]	Taguchi grey relational analysis for process parameter optimization	ANOVA identifies fiber weight as dominant factor	Sisal-epoxy composites	Fiber weight %, curing temperature, pressure	Wind turbine blade material development
[26]	Hand layup and bag molding with Taguchi design	Mechanical testing with filler effects	Sisal, jute, bamboo with CSP and GGBS fillers	Fiber volume fraction and filler type	Automotive, aerospace, renewable energy
[27]	FEA simulation with ANSYS ACP module	FEA results within 9.18% of experimental data	Woven jute fiber-reinforced PLA laminates	LOM 3D printing process parameters	Biodegradable composites for sustainable manufacturing
[28]	Experimental and FEA study with particle reinforcement	Tensile strength improved by fillers, validated experimentally	Jute fiber with cellulose and non-cellulose fillers	Aloe vera gel coating and filler addition	Enhanced mechanical properties for green composites
[29]	Taguchi model for tensile strength of notched jute composites	Experimental tests confirm model predictions	Jute-glass hybrid with notch size and orientation	Fiber orientation and glass volume fraction	Structural composites with notch sensitivity
[30]	Taguchi and grey relational analysis with ANN prediction	ANN predictions closely match experimental data	Sisal-coir hybrid composites	NaOH treatment, compression pressure, temperature	Aerospace and automobile interior parts
[31]	Taguchi L9 design	SEM confirms	Flax-sisal hybrid	Nanofiller wt%,	Mechanical and

Study	Optimization Techniques	Experimental Validation	Fiber Hybridization Effects	Treatment and Fabrication Parameters	Application Relevance
	with nanosilica filler optimization	interfacial adhesion improvements	nanocomposites	reinforcement wt%, alkaline treatment	water retention properties
[32]	Taguchi optimization for cryogenic treatment effects	SEM microstructure analysis of fracture surfaces	Abaca-sisal hybrid composites	Cryogenic treatment time, fiber wt%, load	Aerospace and space applications under extreme conditions
[33]	Taguchi L8 design for PLA/sisal hybrid composites	FTIR, SEM, DSC characterization	Sodium hydroxide treated sisal fibers	PLA infill %, epoxy concentration, fiber content	Sustainable bio-composites for automotive and textiles
[34]	RSM with CCD for fiber orientation optimization	Quadratic models predict tensile and flexural strength	Sisal-carbon fiber hybrid composites	Fiber orientation and composition	Enhanced mechanical properties via orientation control
[35]	RSM with CCD for flax-sisal fiber composites	Statistical models validated experimentally	Flax-sisal hybrid composites	Fiber orientation and fiber proportion	Improved tensile and flexural strength
[36]	Experimental evaluation of sisal-banana epoxy composites	ASTM standard mechanical testing	Sisal-banana hybrid composites	Fiber proportion optimization	Sustainable green composites for structural applications
[37]	Experimental study with fly ash nano-filler	Mechanical property enhancement confirmed	Sisal fiber bio-epoxy with fly ash	Fiber and nano-filler weight fractions	Eco-friendly composites for automotive and construction
[38]	Tensile testing with geometric irregularities	Stress concentration effects analyzed	Sisal-glass fiber composites	Hole size and spacing effects	Design guidance for durability and reliability
[39]	Taguchi L9 design for jute nonwoven fabric	Statistical analysis for tensile and flexural strength	Jute nonwoven fabric composites	Areal density and number of layers	Rigid composites for automotive products
[40]	ANN prediction with experimental validation	SEM fracture analysis	Jute-sheep wool hybrid composites	Fiber loading and chemical treatment	Mechanical and fracture toughness optimization
[41]	Experimental evaluation with Rubik's layer enhancement	Tensile, bending, impact testing	Jute, banana, coconut fiber epoxy composites	Layering sequence and fiber proportion	Sustainable high-performance composites
[42]	Experimental study on hemp and jute	Water absorption and mechanical testing	Hemp-jute epoxy composites	Fiber weight fraction variation	Mechanical behavior for engineering

Study	Optimization Techniques	Experimental Validation	Fiber Hybridization Effects	Treatment and Fabrication Parameters	Application Relevance
	fibers				design
[43]	Grey Taguchi optimization for hybrid fiber composites	SEM wear mechanism analysis	Bauhinia vahlii and kenaf fiber epoxy composites	Fiber wt%, sliding velocity, load	Mechanical and wear properties enhancement
[44]	Experimental tensile testing with fiber orientation	ASTM D3039 standard testing	Sisal-coconut fiber polyester composites	Fiber orientation effects	Lightweight aircraft composite applications
[45]	Experimental study with alkaline treatment	SEM fracture surface analysis	Hemp-sisal fiber epoxy composites	Fiber weight percentage and treatment	Structural and automobile applications
[46]	Hand layup synthesis of glass and natural fibers	Tensile and flexural testing	Jute, flax, coir, hair fiber composites	Fiber type and orientation	Lightweight technical applications

Although there are extensive studies available on natural fiber composites using sisal, jute and different hybrid systems, in most of the previous studies either the research only focuses on experimental characterization, or optimization and numerical techniques are used in isolation. Very limited studies on an integrated framework of experimental testing, Taguchi-based statistical modeling and Finite element Analysis (FEA) validation on the same set of fabricated natural fiber laminates. Furthermore, the literature commonly studies the benefits of hybridization by using different fiber ratios, fillers, or synthetic fiber combinations but lacks a systematic study on sisal-jute laminates using controlled fiber orientations (0-45deg, 0-90deg, and 45-90deg) and stitched laminate fabrication methods. The role of fiber orientation, chemical treatment, and architecture in the laminate, in combination with the statistical predictability and numerical validation is not yet being explored well enough. Therefore, there is an obvious research gap in the development of a comprehensive experimental - statistical - numerical validation approach for sisal, jute and hybrid natural fiber epoxy laminates which is exactly what your work addresses and is tackled by: fabrication, Taguchi optimization, regression - ANOVA modeling, and FEA-based validation.

3. METHODOLOGY

The fig 1 shows methodology that follows a systematic sequence starting from the choice of appropriate natural fibers and epoxy resin as reinforcement and matrix materials. The fibers are then subjected to chemical treatment with alkali and peroxide solutions in order to enhance surface characteristics and bonding ability. After treatment, the bleached fibers are removed and prepared for fabrication. A wooden mold is prepared in order to ensure proper orientation and arrangement of fibers, followed by the fabrication of composite laminates by using prepared materials. Finally, the developed laminates undergo testing to assess the mechanical performance, especially tensile strength.

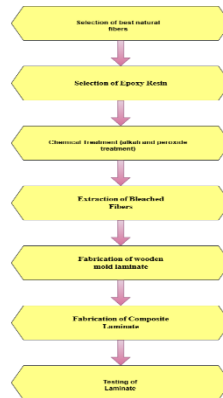


Fig 1 Methodology Flowchart

4. RESULT AND DISCUSSION

This study investigates the tensile behavior of natural fiber composite laminates using experimental testing, Taguchi optimization and Finite Element Analysis (FEA) to validate the model. The work attempts to determine the role of fiber type and orientation on tensile strength and provide a reliable predictive framework for composite performance.

Tensile Strength Results and Experimental Analysis

Tensile testing was performed according to the requirements of ASTM D638-2014 and carried out at a constant crosshead speed of 10 mm/min. The experimental results show large variation in tensile strength with different fiber type and orientation. For Sisal NFC laminates, the 0-45deg orientation resulted in tensile strengths of 10.93, 30.40 and 18.96 MPa, which is a high degree of scatter. This variability implies inconsistent alignment of the fibers and non-uniform impregnation of the resin. In contrast, the 0-90deg sisal laminates showed more consistent performance with values of 17.96, 20.24 and 19.49 MPa, which confirm the fact that fibers oriented closer to the loading direction increase the stress transfer efficiency. The 45-90 degree sisal configuration was again found to have wide variation (28.46, 5.29, 13.55 MPa), showing the complexity of stress distribution in multi-directional laminates. For Jute NFC laminates, the overall tensile performance performance was lower than sisal. The 0-45deg yielded the values of 4.62, 10.50 and 8.38 MPa, and the values of 6.21, 12.88 and 5.46 MPa were obtained for the 0-90deg samples. The 45-90o orientation provided 5.21, 12.51 and 11.17 MPa. These results show weaker bonding between the fibers and matrix and increased sensitivity to processing variations in jute-based laminates. The hybrid laminates Sisal + Jute showed inconsistent behaviour. The 0-45deg orientation gave 3.49, 8.29 and 13.78 MPa whereas the 0-90deg samples gave 3.12, 19.17 and 9.16 MPa. The 45-90deg hybrid laminates were found to be at 16.75, 6.10 and 6.85 MPa. This wide dispersion confirms that hybridization does not automatically ensure mechanical improvement sine fiber compatibility and laminate architecture optimization. Overall, the experimental data confirms that fiber orientation and uniformity of fabrication are dominant in the tensile behavior with sisal composites having excellent strength potential when compared with jute and hybrid systems.

Regression and ANOVA (Taguchi Method) Analysis

Statistical modeling using Taguchi method showed good prediction ability. The result of the regression analysis was that it gave a Multiple R value of 0.9641 and an R2 value of 0.9296 which means that 92.96% of the variation in tensile strength is explained by the chosen parameters. The standard error of 3.5942 is a measure of the predicted values being close to experimental results. The model was further validated through the analysis of variance (ANOVA). The F-statistic of 101.1989 with a p-value of 5.02119E-13 shows far too high statistical significance to conclude that the effect of selected design parameters on tensile strength was found by random variation. The fact that the regression sum of squares (3921.987) is extremely greater than the residual sum of squares (297.1234) proves that the model is strong. These results verify the robustness, reliability, and suitability of the Taguchi-based regression model methodology for the prediction and optimization of the tensile strength of natural fiber composites.

Finite Element Analysis (FEA) Results and Interpretation

Numerical validation was performed via FEA simulation which was performed in ANSYS 2024 R1. The simulation showed the equivalent (von Mises) stress maximum at 26.675 MPa which was apparent to be located at the central region of the specimen. Similarly, the maximum shear stress was 13.349 MPa, and the maximum deformation also occurred in the middle. The deformation and stress distributions were symmetrical and were in agreement with theoretical tensile behaviour, confirming that failure is most likely to initiate in the middle of the gauge region. These results validate the experimental fracture behaviour and the numerical model structural reliability. The slightly higher stress calculated by FEA compared to experimental results can be expected, because idealised simulation conditions without fabrication defects were used.

Comparison and Validation: Experimental vs Taguchi vs FEA

A direct comparison of the three methods confirms strong consistency. For example:

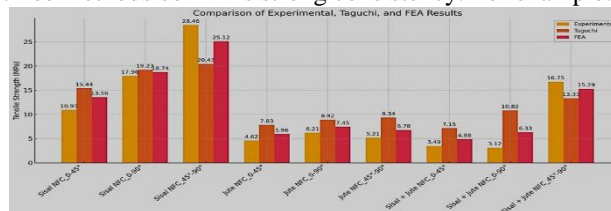


Fig 2 Comparison of Experimental, Taguchi & FEA

The standard deviation values were always lowest for FEA predictions, in the middle for Taguchi, and highest for experimental results, confirming the results that experimental variability is due to fabrication imperfections while Taguchi and FEA provide more stable predictive frameworks.

The results for all three combines to establish that:

- Sisal based laminates have the highest tensile strength potential.
- Fiber orientation near to loading direction (0-90deg) gives improved consistency and performance.
- Hybrid sisal-jute systems need to be further optimized to get the synergistic benefit.
- The Taguchi method is able to predict tensile behavior successfully with a high statistical confidence.

FEA is very powerful in validating stress concentration, deformation behavior and experimental trends. This is an integrated experimental-statistical-numerical framework which greatly enhances the reliability of tensile strength evaluation for natural fiber composites and their future use in sustainable structural materials.

5. CONCLUSION

The tensile strength of the natural fiber composites was varied between 7.83 Mpa and 20.10 Mpa, indicating that the type of fiber and the direction of orientation had a significant effect on the mechanical performance. Sisal laminates showed a significant improvement with alignment and strength increased from 11.17 MPa at 0-45o to 19.17 MPa at 0-90o orientation. Statistical analysis with Taguchi method and ANOVA (high significance, $R^2 \approx 0.93$) proved the high effect of design parameters for tensile strength and also reliable prediction ability. FEA results gave the maximum equivalent stress as 26.675 MPa, maximum shear stress as 13.349 MPa and maximum deformation at the midpoint of the specimen, correctly showing the critical failure zone. The numerical results were found to agree well with the experimental trends, with slight deviations explained by idealized conditions of the simulation. While the Taguchi method gave better predictions for most samples, the behavior of hybrid sisal-jute laminates was inconsistent indicating the need for further optimization. Overall, the combination of experimental testing, statistical optimization, and FEA validation offers a strong framework for designing and developing high-performance natural fiber composites.

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