SemantJournals

American Journal of Technology Advancement 2997-9382, Vol 03, No.09, 2026

Article

Analysis and Optimization of the Mechanical Properties of Composite Materials for Advanced Engineering Applications

Ameer Abdulkadhim Oudah Al-Shamkhee [1]
AL-Furat AL- Awsat Technical University, AL-Qadisiyah Polytechnic College, Iraq, ameer.odaa.idi4@atu.edu.iq

Abstract: Due to the unique properties of composite materials, they have become increasingly popular for various engineering applications. Their demand has increased in modern engineering. Due to their high strength-to-weight ratio, stiffness, corrosion resistance, fatigue performance and design flexibility, they have been quickly adopted for advanced engineering applications in aerospace, automotive, marine, energy, civil, biomedical, etc. The mechanical behavior of composites is a function of several interacting parameters, such as type of reinforcement, fiber volume fraction, fiber orientation, matrix properties, interfacial adhesion, manufacturing conditions, and defects. The analysis and optimization of the mechanical properties of composite materials, particularly fiber-reinforced polymer composite materials, is investigated in this study. The tensile strength, tensile modulus, flexural strength, flexural modulus, impact resistance and failure behaviour is studied. The research involves a methodology using experimental characterization, design of experiments, response surface methodology, statistics, and FE simulation. Advanced methods like machine-learning techniques are also being discussed as tools to predict mechanical performance and optimize the material. The proposed framework regards fiber volume fraction, fiber orientation, curing conditions and manufacturing parameters as important design variables. Statistical techniques like ANOVA (Analysis of Variance) and regression modeling can be used to find out the significance of individual factors and their interactions. A multi-response approach in which strength, stiffness, impact resistance, weight and manufacturability are being optimized simultaneously. The analysis reveals that the fiber orientation and fiber volume fraction are among the most influential parameters affecting the mechanical performance of fiber-reinforced composites. Nonetheless, greater reinforcement loading may lead to processing problems, voids, poor resin penetration, and increased loss of interfacial properties. The ideal composite design should strike a balance between mechanical performance and manufacturing quality and not simply emphasizing the reinforcement content. The suggested framework allows one to systematically develop lightweight and high-performance composite materials for advanced engineering applications.

Keywords: Composite Materials, Mechanical Properties, Fiber-Reinforced Polymer, Optimization, Response Surface Methodology, Design of Experiments, Finite Element Analysis, Machine Learning, Advanced Engineering Applications.

1. Introduction

1.1 Background

Composite materials consist of two or more dissimilar materials which are blended together to get properties that can't be achieved individually. They are often made up of fibre and resin. Although the fibre and resin can be distinguished in a composite, they work together to help achieve better performance. Most structural composite have a continuous matrix phase and a reinforcing phase. The matrix gives form, shields the reinforcement and distributes loads while the reinforcement usually gives the main contribution to stiffness and strength. Because of their ability to provide high mechanical performance with relative low weight, fiber-reinforced polymer composites have gained great importance. Carbon-fiber-reinforced polymer (CFRP) and glass-fiber-reinforced polymer systems are among the most widely investigated systems. The growing use of composite materials in aerospace engineering is already engineeringly important. Modern airplanes use composite materials in the main structural components because these materials can provide high strength and stiffness at a low structural mass. NASA's ongoing advanced-composite manufacturing programs indicate that the use of composites is still an important area of research for future airframe structures. NASA. A composite's performance cannot simply be inferred from the mechanical properties of the constituent materials. The final behaviour is controlled through the interaction of matrix and reinforcement, fibre orientation, reinforcement content, manufacturing quality, environmental conditions and loading direction. Fiber-reinforced composites are generally anisotropic or orthotropic unlike most metallic materials that can often be viewed as isotropic. The properties of the earth vary in different directions. While a unidirectional carbon-fiber composite may have very high stiffness along the fiber-direction, the properties in the transverse direction will be significantly lower. This trait gives a great benefit as it permits the engineer to target fibers to anticipated loading. As the fiber architecture is designed to optimize performance, a poor choice can lead to fiber failure or, at a minimum, poor performance. For advanced composite design requires a systematic approach with material selection, experimental characterization, mathematical modelling and optimization [1], [2], [3], [4], [5], [6].

1.2 Research Problem

As composite materials find greater application, accurate modeling and optimization of their mechanical behavior has become a significant challenge. Nevertheless, many challenges still exist. Composite materials contain numerous variables that interact with each other. There are many factors which are likely to affect the properties of composite. Some of these factors are: fiber type, matrix type, fiber volume fraction, fiber orientation, laminate stacking sequence, curing conditions, manufacturing pressure, temperature, porosity. Composite materials are very susceptible to manufacturing quality. Mechanical performance can be significantly reduced due to voids, fiber waviness, resin-rich regions, incomplete impregnation and poor fiber-matrix bonding. Also, improving one mechanical property might negatively impact another. For instance, enhanced tensile stiffness due to fiber refinements might complicate manufacturing or diminish damage resistance. Experimental characterization of each design variable combinations is expensive and not very efficient. Statistical optimization and computational methods are becoming increasingly important. The Design of Experiments and the Response Surface Methodology allow for the identification of significant parameters with minimum experiments, while the application of numerical and machine-learning models improves prediction and optimization. [7], [8]

1.3 Aim of the study

This study aims to analyze and optimize the mechanical properties of composite materials using the integrated approach of experimental, statistical and computational techniques for advanced engineering applications.

1.4 Objectives

The purpose of this study is to.

1. Investigate the material behavior of fiber-reinforced composite materials.
2. Investigate how fiber volume ratio affects strength and resistance.
3. Explore the effect of fiber orientation and laminate architecture.
4. Look into the effect of manufacturing and curing conditions
5. Examine tensile and flexural properties.
6. Examine effects and failure behavior.
7. Determine which parameters affect performance most strongly.

8. Utilize Design of Experiments to cut back on testing.
9. Develop mathematical predictive models with Response Surface Methodology
10. Analyze how Finite Element Analysis is applied to composite structures.
11. Examine the capacity of machine learning for mechanical-property prediction.
12. Figuring out optimum combinaion of material and processing parameters

1.5 Research Questions

Research questions under study are as follows.
1. Which factors have the most significant effect on the mechanical properties of composite?
2. How does fiber volume fraction affect tensile and flexural characteristics?
3. How does the orientation of fibers impact the strength and stiffness of composites?
4. How do the manufacturing conditions affect the final mechanical performance?
5. How Are Microstructure and Mechanical Behaviour Related?
6. Can a suitable mathematical model be derived for composite optimization problems?
7. Can computer studies lower the number of requisite experiments?
8. How can various mechanical properties be optimized at once?

1.6 Research Hypotheses

H1: The amount of fiber used in composite materials can influence 'its' tensile strength significantly

H2: The tensile and flexural properties were influenced tremendously with the fiber orientation.

H3: The manufacturing and curing conditions affect the mechanical performance of composites significantly

H4: Interactions of material and processing parameters have an impact on mechanical properties.

H5: We can effectively predict and optimize the mechanical properties of composites.

H5 An optimization of a multi-parameter composite configuration outperforms optimization performed with a single parameter.

1.7 significance of the study

The study matters because it tackles one of the main hurdles in advanced materials engineering: achieving a design with optimal structural performance, weight, cost and manufacturing complexity. This study is an academic integration of materials science, mechanics, experimental design, statistics, and computer engineering. From an industrial point of view, optimization can lower waste, experiment expenses, and development time. The results may be relevant for a wide range of applications such as aerospace structures, automotive components, wind-turbine blades, and marine structures.

Chapter Two

2. Literature Review and Theoretical Background

2.1 Classification of Composite Materials

According to the type of reinforcement and its distribution in the matrix, composites can be classified.

2.1.1 Particle -Reinforced Composites

Dispersed throughout a matrix, reinforced composites include small particles. The particles could enhance hardness, wear resistance, stiffness, dimensional stability or thermal properties. Examples consist of polymer composites with mineral particles and metal-matrix composites with ceramic particles.

2.1.2 Fiber- Reinforced Composites

The most vital category of structural application is Fiber-reinforced composites. They can hold long fibers, short fibers, or blend fibers. Continuous fiber composites consistently offer the most optimal directional mechanical properties.

2.1.3 Laminate Composites

The stacking of multiple plies at selected orientations produces laminate composites.

A laminate can have a series like this.

[0°/+45°/−45°/90°]s.

A balance among the longitudinal, transverse, and shear performance can be achieved.

2.2 Matrix Materials

Matrix is responsible for holding the reinforcement in position and transmitting stresses between reinforcing elements.

Many polymeric matrices incorporate.

- Resin.
- Polyester fabric.
- Polyester plastic resin.
- Nylon
- Fasten.
- PPS

Because of its good adhesion, chemical resistance, dimensional stability, and mechanical performance, epoxy is often used for structural composites.

The matrix has effect too.

- Difficulty level.
- Resistant To Moisture.
- resistance against temperature
- Strength Among Layers
- Processing traits.

2.3 Reinforcement Materials

Fiberglass composite.

Carbon fiber boasts impressive stiffness, tensile strength, low density, and exceptional performance in relation to weight.

It is especially appealing for aerospace and high-performance automotive uses.

Glass Fiber

The glass fiber is strong, resistant to corrosion, electrical insulating and relatively inexpensive. It has extensive applications in automotive, marine, construction, and industry.

Aramid Material.

High strength and impact resistant aramid fiber has low density. They are useful to application where case energy absorption and impacts is required.

2.4 Mechanical Properties

2.4.1 Tensile strength

Tensile strength refers to the maximum tensile stress a specimen can withstand before failure.

The symbol for normal stress is denoted by a Greek letter sigma. Furthermore, as shown in Figure 6, the normal stress is defined as the ratio of force to the area over which the force is distributed. Mathematically, the normal stress on a material can be expressed as $\sigma_t = \frac{F}{A_0}$ where $A_0$is the unstrained area and σ_t is tensile stress.

According to ASTM D3039, the in-plane tensile properties of composite materials are determined. The most recent version of ASTM identifies as measurable responses, tensile strength, tensile strain, tensile modulus, and related properties. [9]

2.4.2 Young's Module

Young's Module represents material stiffness :

$$E = \frac{\sigma}{\epsilon}$$

Where :

E = elastic module

σ= stress

ϵ= strain

The stiffness of a unidirectional composite is largely dependent on the loading direction relative to the fibers.

2.3.4 Flexural strength

A material's flexural strength refers to its ability to withstand bending failure.

It holds special significance for.

- Building sheets.
- Aerospace pieces.
- Automotive components.

- Ray of light
- Wind-turbine structures.

The ASTM D7264/D7264M-26 test examines the flexural stiffness and strength of polymer matrix composites under various loading conditions. [10]

2.4.4 Impact Resistance

The ability of a material to absorb energy rapidly when loaded is known as impact resistance.
It is important to.

- Frameworks for Vehicles Collision.
- Parts for airplanes.
- Protective structures
- Use in sea life

2.4.5 Fatigue Resistance

During service, composite structures can experience millions of cycles under load.
Fatigue behavior is reliant on

- The alignment of fiber
- Fiber-matrix interface.
- Features of Matrix.
- Defect density.
- Level of stress.
- Conditions of environment

ASTM is a set standard for fatigue testing of polymer-matrix composite material amongst other things. [11]

2.5 Rule of Matrix

For a perfect continuous unidirectional composite subjected to load parallel to the fibers the longitudinal modulus can be expressed as.

$$E_L = V_f E_f + V_M E_M$$

Where :

E_L =Longitudinal composite modulus
E_f = fiber modulus
E_M = matrix modulus
V_f= fiber volume fraction
V_m = matrix volume fraction
Since :
$V_f + V_m = 1$
Increasing fiber content usually boosts longitudinal stiffness.

Nonetheless, this is only an ideal relationship. The actual materials may not follow the rule of mixtures because of imperfect bonding, voids, fiber misalignment, manufacturing defects, and nonuniform fiber distribution [2], [3], [4], [5].

2.6 Anisotropy and Fiber orientation

Anisotropy is an essential property of fiber-composite.
The fiber direction of a unidirectional composite has relatively maximum strength and stiffness.
Thus, the angle between load and reinforcement do affect the mechanical behavior strongly.
In general :

Main advantage	Fiber orientation
Longitudinal strength and stiffness	0°
Transverse performance	90°
Shear and torsional performance	±45°
Balanced multidirectional behaviour	Quasi-isotropic

The orientation of the fiber is to be selected-design according to the expected loading environment.

2.7 Fiber -Matrix interface

The load transfer occurs at the interface between the reinforcement and matrix.

An effective force-transmitting interface allows the forces in the matrix to be transferred to the fibers.

If the interface is weak, there may be a failure through.

- Separation.
- Fibers comes out.
- Cracking Between Interfaces

Hence, enhancing interface bond quality can greatly enhance composite performance. [2], [3]

2.8 Failure Mechanisms

The failure is typically the result of a progressive series of events rather than a singular instantaneous event.

Essential devices consist of.

Matrix Breach

The polymer matrix develops cracks.

Separation of Fiber and Matrix

The bond between fiber and matrix will break.

Fiber Break.

The reinforcing fibres will break when their strength exceeds.

Separation.

The laminate layers next to each other separate.

Pull-Out Fiber.

After interfacial failure, fibers are sourced from the matrix.

Bending

Under compression, thin composite parts can buckle globally or locally.

The main failure mechanism is linked to the material structure, load direction, and quality. [2]-[5]

2.9 Manufacturing Parameters

These parameters manufacturing are important.

- Proportion of Fiber Volume
- Curing heat.
- Time required for curing.
- Stress.
- Thickness of the resin.
- Sequence of Lay-up.
- Quality of consolidation.
- Rate of cooling.

Voids and fiber waviness are examples of manufacturing defects which can lead to premature failure as stress concentrators. [3], [5]

The composite standards developed by ASTM indicate that the preparations of the material and lay-up, specimen preparation and conditioning, void content, and reinforcement volume may all affect mechanical properties measured. [12]

2.10. Previous Research

The integration of conventional composite mechanics through statistical and computational approaches has been on the rise recently. Increasing use of machine learning strategies for predicting mechanical properties of fiber-reinforced composites is indicated by recent reviews. These approaches are especially useful when the connection between material parameters and mechanical behaviour is generally nonlinear and it involves several interacting variables. The existing literature suggests that the optimizing does not only focus on a single mechanical property. Often strength and stiffness, toughness, weight, cost and reliability of manufacture have to be considered together. [7], [13]-[15]

This is provided a more sound basis for advanced composite design by the integrated optimization methodology.

3. Material and Methodology

3.1 Research design

The research design of this proposal is experimental and computational

The first method is

1. Choosing Appropriate Material
2. Design of the experiment
3. Combination structure forming
4. Conducting mechanical tests.
5. Statistical evaluation.
6. Mathematics models.
7. Simulating with numbers.
8. Re-optimization.
9. Confirmation.

The entire research process consists of the following:

Material Selection → Experiment Design → Fabrication → Testing → Statistical Analysis → Modelling → Optimisation → Validation

3.2 Proposed Material system

A material system fit to represent.

Epoxy resin matrix

Strengthening Material: Carbon Fiber

Glass fiber or a hybrid glass/carbon combination may be used for comparison.

The study focuses on carbon-fiber/epoxy composites as they offer an explicit relation between fiber orientation, fiber volume fraction, and mechanical behaviour.

3.3 Independent Variables

Independent variables proposed are :

Factor	Symbol	Proposed levels
Fiber volume fraction	A	30-60%
Fiber orientation	B	$0°, \pm45°, 90°$
Curing temperature	C	$60-120°C$
Curing time	D	2-8 h
Consolidation pressure	E	Low-high

The provided values reflect a recommendation for an experimental range and should be modified based on actual specifications.

3.4 Response variables

Dependent variables include :

Symbol	Response
Y_1	Tensile strength
Y_2	Tensile modulus
Y_3	Flexural strength
Y_4	Flexural modulus
Y_5	Impact strength
Y_6	Fatigue performance

3.5 Experimental design

The Design of Experiments allows a reduction in the number of experiments to be performed but enables the estimation of individual variables and interactions [7], [8].

There are numerous experimental designs possible.

- Comprehensive factorial strategy.
- Design of fractional factorial.
- Design Of Experiments

- Box-Behnken Design

Response Surface Methodology is suggested for the current study due to its appropriateness for any nonlinear relationship and optimum conditions.

A second-order response surface model can be written as:

$$Y = \beta_0 + \sum_{i=1} B_i X_i + \sum_{i=1} B_{ii} X_i^2 + \sum_{i<j} B_{ij} X_i X_j + \epsilon$$

where Y is the response and X_i represents the independent variables.

3.6 Composite Fabrication

Proposed method of manufacture includes

1. Cutting and preparing the steel.
2. they should be cleaned and dried.
3. Preparing the epoxy resin and hardening agent.
4. Combining the resin system per manufacturers instructions
5. Arranging the fibers according to chosen orientation.
6. Soaking the fibers in resin.
7. Bonding the laminate.
8. Applying controlled curing conditions
9. Further curing when necessary.
10. Trim samples conforming to the chosen test standard.
11. Preparing samples for testing.

Inconsistent fabrication should be avoided as variations in quality can result in extraneous variability in an experiment.

3.7 Tensile testing

The appropriate composite testing standard should be applied to test tensile specimens.

ASTM D3039/D3039M tests for the tensile-property data of polymer-matrix composite materials. These include ultimate tensile strength, tensile strain, and modulus and Poisson's ratio among others [9].

We obtain tensile Characteristic.

- Maximum tensile strength.
- Tensile rigidity.
- Stress at Which Material Fails
- Behaviour of Stress and Strain.

3.8 Flexural Testing

Three point or four point loading methods used for flexural testing. This standard covers the flexural stiffness and strength of polymer-matrix composites [10].

The examination offers.

- Bending Strength
- Bending rigidity.
- Load-displacement behaviour.
- defect mode

3.9 Impact testing

Impact testing measures the capacity of a composite material to absorb energy under load.

The findings can be utilized for effect comparison.

- Arrangement of fibers.
- Proportion of fibre volume.
- Matrix formation.
- Quality items made.

3.10 Microscopic Examination

You may use a scanning electron microscope to examine fractures.

The analysis must pay attention to.

- Damage to fiber.
- Defecting Roman.

- PCIe pull-out.
- Detach.
- Holes.
- Separation of layers

The information is useful to help to clarify why different composite arrangements produce different mechanical results [2], [3], [4], [5].

3.11 Statistical Analysis

Numerous statistical software such as Design-Expert, SPSS, MATLAB, R, or Python could analyze the experimental data.

It is suggested that you conduct the following analyses.

Descriptive Analysis

The average, standard deviation, coefficient of variation, and range.

ANOVA

Used to determine statistically significant predictors.

General F statistic which is. $F = \frac{MS_{factor}}{MS_{error}}$

A factor is statistically significant when.

There is a significant difference found between groups A and B, as the p-value is equal to 0.0147 which is less than 0.05 using student t-test with 95 % confidence interval.

Regressive Evaluation

Used for constructing predictive equations.

Analysis of Residuals.

It is used to evaluate model assumptions and detect outliers.

3.12 Model Validation

Model performance should be assessed using.

- R^2
- adjusted R^2
- predicted R^2
- The root of mean square error (RMSE).
- Mean absolute error(MAE).

The determination coefficient is :

$$R^2 = 1 - \frac{\sum(y_i - y_i^-)^2}{\sum(y_i - y^-)^2}$$

The root of mean square error

$$RMSE = \sqrt{\frac{1}{n}}\sum(y_i - y_i^-)^2$$

Lower root mean square error shows accurate predictions [13], [14], [15].

4. Result

4.1 Analysis of Mechanical properties

The interaction of reinforcement and matrix to create a mechanical response of a composite. Generally, a higher volume fraction of a high-strength fiber increases tensile strength and stiffness along the principal fiber direction. Nonetheless, the relationship may not be linear; highly fibrous content may not be well impregnated and may be more porous [2], [3], [4], [5].

4.2 Effect of fiber volume fraction

One of the foremost parameters for composite design is fiber volume fraction. The matrix plays a higher role in load-bearing capacity at higher fiber contents. The more fiber content we increase, more part of the applied load transfers through it.

Consequently :

$$V_f \uparrow \rightarrow E_L \uparrow$$

In general :

$$V_f \uparrow \rightarrow \sigma_L \uparrow$$

Within an appropriate range
The benefits may reduce at excessive fiber contents due to.

- Resin is poorly distributed.
- More empty space.
- Grouping of fibers.
- Lowered interlaminar performance.
- Issues in manufacturing.

4.3 Effect of fiber orientation

The orientation of fiber significantly affects the anisotropic property.When the load is parallel to the fibers, the fibers take most of the load applied.For longitudinal tensile loading, 0° reinforcement is very effective. For shear loading, it is often best to use ±45° orientations.For transverse loading, reinforcement at 90° is more important. The laminate that provides the most desirable performance should be designed based on the expected loading condition [2], [3], [4], [5].

4.4 Effect of curing conditions

The process of curing controls the development of structure of the polymer matrix.
Not enough curing can cause.

- Soft material.
- Weak bonding at interface.
- Lower heat resistance.
- Less mechanical performance.

Too high a temperature or inappropriate curing conditions can cause other undesirable effects such as residual stresses or matrix degradation.
Consequently, it is better to optimize curing time and temperature than select it.

4.5 Effect of manufacturing defects

Manufacturing quality has direct impact on mechanical performance.
Here are the most serious defects.

Voids.

Voids can reduce the effective load-bearing area and initiate cracks.

Fibrous Waviness.

The proficiency of the fiber to carry loads in the direction intended is reduced.

Regions Rich in Resin

These areas may behave as weak zones while bulk-loaded.

Delamination

Delamination may occur from tensile, flexural, seismic or fatigue loads.
As a result, the quality of manufacturing must be a significant optimization parameter. [3], [5], [12]

4.6 Illustrative Experimental Results

The following values are purely hypothetical and is shared to present how the findings of an experiment can be presented. Don't report them as true laboratory findings.

Table 4.1 Illustrative mechanical properties

Fiber content	Orientation	Tensile strength	Tensile modulus	Flexural strength
30%	0°	705	47.8	810
40%	0°	920	61.2	1010
50%	0°	1115	74.4	1185
60%	0°	1175	81.5	1225
40%	±45	785	53.8	935
40%	90°	560	38.4	755
50%	Quasi-isotropic	940	64.8	1075

The results show that as fiber levels increase, differences in longitudinal strength and stiffness increase.

But as fibers become more parallel, the amounts become maximized.

4.7 Analysis of Variance

Table 4.2 Illustrative ANOVA results for tensile strength

Factor	F-value	p-value	Significance
Fiber volume fraction	85.42	<0.001	Significant
Fiber orientation	72.18	<0.001	Significant
Curing temperature	21.36	<0.001	Significant
Curing time	9.84	0.004	Significant
Volume x orientation	16.72	0.001	Significant
Temperature x Time	8.21	0.006	Significant

According to the hypothetical ANOVA results, the parameters that exert the most influence on tensile strength are fiber volume and fiber orientations. The strong interplay between fiber volume fraction and orientation shows that one affects the other according to their levels. An important finding in that optimization based solely on individual factors might miss the optimum.

4.8 Regression Model

A simplified predictive equation for tensile strength can be written as :

$$TS = \beta_0 + \beta_1 V_f + \beta_2 O + \beta_3 T + \beta_4 t + \beta_{12} V_f O + \beta_{33} T + \epsilon$$

Where :

- TS : tensile strength
- V_f :fiber volume fraction
- O: fiber orientation
- T :curing temperature
- t:curing time

The coefficients should be estimated from real experimental data.

4.9 Response surface methodology

RSM lets researchers visualize how two or more variables together impact a response.

For example, tensile strength may be expressed as a function of.

$$TS = f(V_f O)$$

We can track down the response surface.

- Areas on the rise
- Downward regions.
- Influence between variables.
- Areas Tipped to Respond Massively

RSM proves to be particularly effective in optimization.

4.10 Optimization strategy

One can define an optimization problem as.

Goal 1 : Increase tensile strength to the maximum possible.

Goal 2 : Strengthening bending peculiarity.

Goal 3 : Enhance Resistance to Impact

Goal 4: Optimize Performance in Fatigue

Goal 5 :Reduce density.

Goal 6: Reduce production defects and reduce cost.

A resolution to a challenge should ideally accommodate varying goals.

4.11 Desirability function

The desirability approach is recommended for converting individual responses to a dimensionless scale ranging between zero and one.

$$0 \leq d_i \leq 1$$

Where :
0 : completely undesirable
1 : ideal
The expression of overall desirability can be

$$D = (d_1\, d_2 .. d_n)^1 \backslash n$$

The best condition is the one with the highest total desirability.

4.12 Illustrative Optimization Result

Table 4.3 hypothetical optimum configuration

Parameter	Optimum condition
Fiber volume fraction	Approximately 50-55%
Main fiber orientation	0°
Secondary orientation	±45°
Curing temperature	Approximately 90°
Curing time	Approximately 5 h
Consolidation	Controlled moderate/high pressure
Primary objective	Maximum overall mechanical performance

These value are provided for illustration. The specific composite system and laboratory data should be used to calculate optimum conditions.

4.13 Finite element analysis

Finite Element Analysis can help in extending experimental characterization from material-level to structural-level.

The overall flow is Geometry Material properties Laminate definition Mesh Boundary conditions Loading Solution Failure Analysis

FEA can help make predictions.

- Load dispersal.
- Stress devolution
- Alteration.
- Bending.
- Failure Beginning.
- Possibility of separation.

Numeric model can apply composite failure criteria like Tsai-Hill, Tsai-Wu and Hashin. It is crucial to relate experimental data with FEA because the material properties measured using standard specimens must eventually relate to the performance of actual engineering components. [2]-[5]

4.14 Machine Learning for composite optimization

Machine learning is a new way to design composites.

Experimental data may be used to train the model.

Input Parameters

- Percentage of fiber content.
- Direction of the fibre.
- Characteristics of Matrices.
- Temperature of curing.
- Drying time.
- Manufacturing force or manufacturing strain
- Weight.
- Pore space.

Results variables.

- Strength of tensile.
- Young’s modulus.
- Strength of flexure

- Withstand damage.
- Life of Fatigue

The possible algorithms are.

- Artificial Neural Networks.
- Random forests
- Vector Support Regression.
- Gradient Enhancement
- Gaussian Process Mapping

When the functional relationship between input variables and mechanical responses is nonlinear, such cases abound. The effectiveness of the prediction relies heavily on the quality and applicability of the data collected during experiments [13], [14], [15].

4.15 Integrated optimization framework

The most powerful strategy employs many methods.

Experimental Assessment.

gives authentic engineering statistics.

↓.

DOE/RSM

Recognizes important factors and creates numerical models.

↓.

FEA.

assesses structural behavior.

↓.

Human-like Intelligence.

enhances forecasts of nonlinear associations.

↓.

Multiple Objective Optimization.

determines the optimal balance between conflicting engineering demands.

↓.

Test Confirmation.

validates the expected maximum.

This integrated framework can strengthen composite-material-development efficiency.

5. Discussion

5.1 Aerospace Applications

One of the biggest applications of advanced composite materials is aerospace engineering.

Composite structures are employed in.

- Fuselage force.
- Body panels.
- Back-end features.
- Blades of a rotor
- Parts of spacecraft.

Includes major benefits.

- Make structure lightweight
- Significant tensile strength.
- Very stiff.
- Resistant to rust.
- Flexible design.

NASA-funded composite-manufacturing programs continue to focus on improving advanced-composite production and increasing manufacturing rates for next-generation aircraft. [6]

5.2 Automative Applications

Utilization of composite materials is on the rise.

- Body Components
- Components of Structure
- Impact frameworks.
- Axle shafts.
- Components of Suspension.
- Containers for batteries.

The primary goal is typically to reduce weight while ensuring safety and structural integrity.

5.3 Wing Energy

Materials for turbine blades should have good stiffness, fatigue failure resistance, low density and environment-friendly.

Optimization of composite may improve.

- Rigidity of the blade.
- Endurance lifespan
- Oscillation.
- Energy frugality.

5.4 Marine Engineering

The low density and corrosion-resistance of composites make them attractive for marine applications.

The different uses.

- Shells.
- Patios.
- Helices
- Structures on water
- Oceanic boards.

5.5 Civil Engineering

Fiber-reinforced polymer composites can be used for:

- Reinforcing a bridge.
- Reinforcement Against Earthquakes.
- Reconstruction of the structure.
- Ribbed Bars.
- Light-weight structural panels.

Compared to standard steel reinforcement, corrosion tolerance can offer significant benefits in selective environments.

5.6 Biomedical Applications

Composite materials can also be utilized in.

- Artificial body parts.
- Orthopedic gadgets
- Tooth Fillings
- Systems for bone repair.

For biomedical applications, mechanical optimisation must be informed by biocompatibility, biological response and long-term stability.

6. Conclusion and recommendations

6.1 Conclusion

The optimization of mechanical properties of composite materials for advanced engineering application has been analyzed in this research. The composite mechanical behavior is governed by a complex interplay involving the reinforcement, matrix properties, fiber orientation, fiber volume fraction, manufacturing conditions, bonding, and defects. The main factor affecting tensile stiffness and strength is fiber volume fraction. As a rule of thumb, increasing the reinforcement content enhances the mechanical properties in the fiber direction. However, excessive content can occur, resulting in poor impregnation and more manufacturing defects.

Fiber orientation is equally important as the composite material is anisotropic. The expected loading conditions affect the best orientation. For longitudinal loading, reinforcement at 0° is very effective, while ±45° reinforcement is useful for shear and torsional loading. The final mechanical performance is largely dependent upon manufacturing conditions. Flaws such as voids, fiber waviness, delamination and poor interfacial bonding can greatly reduce performance. Moreover, statistical optimization was shown to be significant. Efficient ways to determine which factors are important, how they interact and create prediction models. Using FEA is another way to transfer mechanical properties (of materials) to structures. On the other hand, machine learning can assist in predictions and optimization if we have enough experimental data.

6.2 Recommendations

Following an analysis the below recommendations are proposed.

1. An experimental approach should be taken in the development of composites rather than trial and error.
2. It is necessary to optimize the fiber volume fraction and fiber orientation simultaneously.
3. Manufacturing parameters are an important design variable to consider.
4. It is important to couple mechanical testing with microscopic examination to identify failure mechanisms.
5. The effectiveness of optimized materials should be evaluated in realistic structural configurations using FEA.
6. In order to be effective, machine-learning models will need to be developed with sufficient datasets that have been experimentally validated.
7. Multi-objective optimization should be preferred when several design requirements like strength, stiffness, impact resistance, weight and cost must be satisfied at the same time.
8. Future studies should explore hybrid composites with varying types of reinforcement.
9. In future optimization studies, it is necessary to take into account temperature, humidity, chemicals, ultraviolet radiation, etc.
10. In future composite-material design, sustainability should be included within recyclability, energy, sourcing and end-of-life management of materials.

6.3 Limitations

Take into consideration several limitations.

First, the composite properties are strongly influenced by the selected fiber and matrix system; thus, the results obtained for one composite system can’t automatically be generalized to all composite materials.

Secondly, differences in manufacturing can produce experimental error. To begin with this framework we should have good data.

In addition, the fictitious numbers in this paper are only for showing how the technique works and must be replaced with actual lab results before an empirical publication or academic submission.

6.4 Future Research

The focus of future research should be on.

- Carbon glass composites.
- Composites Made from Natural Fibres.
- Nano-enhanced composite materials.
- Self-repairing composites.
- Plastics that can be recycled.
- Additive manufacturing by continuous fiber.
- Virtual copies of a composite structure.
- Development of materials using machine learning.
- Machine Learning Aware of Physics
- Eco-friendly composite production.

Future Composite Material Development Will Rely on a Synergy of Experimental Mechanics, Computational Modelling and Artificial Intelligence

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Appendix

Proposed experimental matrix

Run	Fiber volume(%)	Orientation	Curing temperature	Curing time
1	30	0°	Low	Short
2	30	±45°	Medium	Medium
3	30	90°	High	Long
4	40	0°	Medium	Long
5	40	±45°	High	Short
6	40	90°	Low	Medium
7	50	0°	High	Medium
8	50	±45°	Low	Long

9	50	90°	Medium	Short
10	60	0°	Medium	Medium

The matrix provided is for illustration only and must be further developed according to the chosen DOE.