





# Propuesta de material compuesto para mejorar la eficiencia de las palas de los generadores eólicos en Cuba

## Proposal of composite material to improve the efficiency of wind turbine blades in Cuba

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<sup>2</sup> Escritura – borrador original, redacción, revisión y edición

**Resumen** – El presente trabajo se centra en mejorar la eficiencia de las turbinas eólicas en Cuba mediante el desarrollo y la fabricación de materiales compuestos. Se utilizó una configuración de lámina de refuerzo de fibra de vidrio  $[0^\circ/90^\circ/0^\circ/90^\circ]_s$  para las palas de las turbinas. Se llevaron a cabo investigaciones exhaustivas sobre el diseño aerodinámico, la selección de materiales y la simulación estructural para optimizar el rendimiento de las turbinas. Se emplearon técnicas avanzadas, como la simulación computacional con ANSYS y eLamX2, para predecir el comportamiento de los materiales compuestos bajo diversas condiciones operativas. Estas técnicas permitieron una comprensión más profunda de cómo estos materiales reaccionarían en diferentes escenarios, lo que a su vez permitió mejoras en el diseño y la fabricación. La investigación se basó en la necesidad de Cuba de diversificar su matriz energética y reducir su dependencia de los combustibles importados. Además, se reconoció la necesidad de aprovechar el potencial eólico de Cuba, que hasta ahora ha sido en gran medida subutilizado. Se demostró que la fabricación de palas utilizando un método mixto de infusión y compresión al vacío es efectiva, lo que resulta en palas eólicas más eficientes y duraderas. Este avance tiene el potencial de mejorar significativamente la eficiencia de las turbinas eólicas en Cuba. El trabajo contribuye de manera significativa a la transición energética de Cuba hacia fuentes más sostenibles y eficientes. Proporciona una base sólida para futuras investigaciones en el campo de la energía eólica y la ingeniería de materiales.

**Palabras clave:** eficiencia energética, materiales compuestos, energía eólica, simulación, turbinas.

**Abstract** – The present work focuses on improving the efficiency of wind turbines in Cuba through the development and fabrication of composite materials. A  $[0^\circ/90^\circ/0^\circ/90^\circ]_s$  fiberglass reinforcement sheet configuration was used for the turbine blades. Extensive research on aerodynamic design, material selection, and

structural simulation was conducted to optimize turbine performance. Advanced techniques, such as computational simulation with ANSYS and eLamX2, were employed to predict the behavior of composite materials under various operating conditions. These techniques allowed for a deeper understanding of how these materials would react in different scenarios, which in turn allowed for improvements in design and manufacturing. The research was based on Cuba's need to diversify its energy matrix and reduce its dependence on imported fuels. In addition, it recognized the need to take advantage of Cuba's wind potential, which until now has been largely underutilized. The manufacture of

blades using a mixed method of vacuum infusion and compression was demonstrated to be effective, resulting in more efficient and durable wind blades. This advance has the potential to significantly improve the efficiency of wind turbines in Cuba. The work contributes significantly to Cuba's energy transition to more sustainable and efficient sources. It provides a solid foundation for future research in the field of wind energy and materials engineering.

**Keywords:** energy efficiency, composite materials, wind energy, simulation, turbines.

## Introduction

The transition to cleaner and more sustainable energy sources is a global imperative to mitigate the effects of climate change and reduce our dependence on fossil fuels (IRENA, 2021). Within this context, wind energy emerges as one of the most promising renewable alternatives, evidenced by its growing adoption in leading countries such as the United States, Germany, China, India and Spain. The significant contribution of this energy source to the renewable energy mix, as in the case of Spain where it covers 18% of electricity demand, underlines its potential and relevance. The remarkable growth of the wind sector, with the installation of 77.6 GW of new capacity in 2022, bringing the total installed capacity to 906 GW, highlights the accelerated expansion and the need to optimize this energy source (Alex, 2023).

Over the next five years, significant growth in global onshore wind power capacity is expected. North America is projected to add 60 GW, led by the United States. Europe, with Germany, Spain and the UK leading the way, will also see significant growth. Africa and the Middle East will add 17 GW, with South Africa and Egypt as major contributors. Latin America will add 26.5 GW, mainly from Brazil, Chile and Colombia. Global wind power capacity is expected to reach a milestone of 2 TW in just seven years, representing an increase of 143 GW (13% y-o-y) in projections for 2023-2030 compared to previous estimates (Alex, 2023).

Cuba is promoting sustainable development and the adoption of clean technologies to combat climate change. Biomass is the main source of renewable energy in the country, representing 96.42% of the total. Solar and wind energy contribute 0.24% and 0.12%, respectively, and other renewable sources are being explored. The energy transformation in Cuba has led to the creation of wind turbine fields, highlighting the formation of the National Wind Energy Group in 2005 and the construction of the Los Canarreos wind farm with a capacity of 1.65 MW. Currently, there are four wind farms in operation with a total capacity of 11.8 MW, and two new wind farms are under construction that will contribute an additional 101 MW. A third farm under development will contribute 50 MW.

The location of these farms offers benefits such as diversification of wind sources, resilience to weather events, and better integration with the national power grid. To maximize wind potential, the focus is on advanced technologies for turbine design, optimized for local climatic conditions

and with minimal maintenance. This also promotes local innovation and reduces dependence on imported technologies (Li, 2023; Quesada Marquetti *et al.*, 2024; Reyes *et al.*, 2022; Sánchez Torres & Rodríguez Ramos, 2021; Santos & González, 2019; Soto Calvo *et al.*, 2024; Suárez Rodríguez & Beatón Soler, 2007).

Due to the importance and transcendence of the subject for the country, the authors of this work have defined as scientific problem: The need to improve the durability and efficiency of wind turbine blades in Cuba.

- Object of research: Design and manufacturing processes of composite materials.
- Field of action: Design and manufacturing methodologies of Composite Materials for Vertical Wind Generator blades.
- The general objective of the research is to design a composite material to increase the efficiency and durability of the blades in wind generators in Cuba.
- It is adopted as a working hypothesis that: The application of advanced composite materials, combined with computational simulation techniques, will result in wind turbine blades with significant improvements in aerodynamic performance and resistance to adverse conditions, increasing the energy efficiency of wind turbines in the Cuban context.

## Materials and Methods

A complex interaction of different research methods (theoretical and empirical) was used, by means of the historical and logical method; the current trends on the world energy transition towards renewable energy sources were determined, with particular emphasis on the Cuban context in terms of wind energy. Its application was possible thanks to the existence of national and international experience on the subject. The modeling method, very important to obtain the artificial representation of the proposed model, as well as the procedure for its implementation.

As for the empirical methods, thickness measurements were used in both manufacturing methods, manual and mixed, in order to determine which one guarantees an optimum proportion of 50% fiberglass and epoxy resin with the smallest cross-sectional area of the fiber. Fiber and resin volume measurements were taken to determine the percentage of air bubbles in the material once manufactured, which can affect the quality, design, performance and application of the material.

The following procedures were used in association with the different methods:

**Literature analysis:** a comprehensive review of the scientific and technical literature related to composite materials, fiberglass, epoxy resins and applications in the wind industry is performed. This provides a solid understanding of the current state of knowledge, available technologies and relevant research areas.

Specific requirements and constraints for on-deck wind blades are established, taking into account aspects such as mechanical strength, durability, weight and aerodynamics. In addition, challenges associated with energy efficiency and operating conditions are considered.

**Material selection and preliminary design:** the most suitable composite materials are chosen, taking into account their mechanical properties, fatigue resistance, behavior under dynamic loads, etc. A preliminary design of the wind blades is carried out, considering aspects such as shape, size and arrangement of the fiberglass and epoxy resin layers.

**Performance analysis through simulation and modeling:** simulation and modeling tools are used to predict the structural and aerodynamic behavior of wind blades under different wind and load conditions. This allows the design to be optimized to maximize energy efficiency and minimize potential problems such as fatigue and vibration.

**Synthesis of results and design optimization:** the results of simulations and experimental tests are analyzed to identify areas for improvement in the design. Adjustments are made to the design and materials used in order to improve the energy efficiency and lifetime of the wind blades.

## Results and Discussion

To carry out the study, it was decided to use pre-existing and widely validated profiles. Among these, the NACA 0018 airfoil stood out for its versatility, being suitable for both vertical axis wind turbines (VAWT) and horizontal axis wind turbines (HAWT) (Damiola *et al.*, 2024; Güler *et al.*, 2024; Lam & Leung, 2018; Lesovoy *et al.*, 2024; Michna & Rogowski, 2022). This choice gave us direct access to crucial information from an aerodynamic point of view, avoiding the need for in-house testing, which is essential when designing a profile from scratch, which allowed the authors to characterize the material from a mechanical point of view, in addition to evaluating its performance by means of computational simulation.

The thin airfoils, although aerodynamically advantageous, were evaluated to ensure their resistance, these tests are necessary to know the operational performance in function of a series of operation parameters depending on the work context as shown in table 1, which is based on wind studies carried out in Cuba. The realization of these simulations guarantees greater efficiency without sacrificing the strength of the blade structure, saving in material resources of production in physical prototypes.

**Table 1.** Atmospheric parameters considered for Cuba

Pressure atm	Density	Viscosity	Wind	Subject
101325 [Pa]	1,225 [Kg/m <sup>3</sup> ]	1.4 * 10 <sup>-5</sup> [Kg/m-s].	8 [m/s].	288.15 [K]

### Study of the mechanical properties of the material

The study focused on the mechanical characterization of unidirectional fiberglass sheets. Mechanical properties were determined in 0° and 90° orientations, evaluating how the manufacturing process affected these properties. Rigorous quality control was implemented by fabricating the specimens according to the recommendations of ASTM D3039 (ASTM D3039, n. d.).

For the mechanical tests, the specimens have 0.11 mm glass fiber layers, compacted with an EPO 200/813 epoxy matrix in a 2:1 ratio. The solidified matrix distributes forces, maintains fiber

alignment and protects the fibers. Two methods of fiberglass specimen fabrication were compared: mixed infusion and manual infusion. Mixed infusion involved stacking layers of fiber, applying liquid epoxy resin and compacting them under vacuum to remove air and increase stiffness. The manual method involved depositing resin between the layers without vacuum, curing at ambient pressure and temperature.

Both processes began with cutting the raw material into sheets of specific dimensions for tensile testing at 0° and 90°. The mixed infusion process required manual arrangement of fibers and resin, followed by vacuum infusion, which provided superior compaction and a stiffer matrix. On the other hand, the manual method, although simpler, did not use vacuum and allowed the composite to cure at ambient pressure. After 24 hours of drying, the specimens were demolded, ready for mechanical testing. This study is fundamental to understanding the influence of the manufacturing method on the mechanical properties of composite materials and optimizing their use in structural applications.

### Specimen preparation

A total of 3 tensile specimens were cut with a 0 degree orientation, each with dimensions of 15 mm x 250 mm, and 3 tensile specimens were made at 90°, with dimensions of 25 mm x 175 mm. In addition, from the 90° oriented plate, additional cuts were made to fabricate the tabs according to the recommendations established by the applicable ASTM D3039 standard, as shown in Table 2.

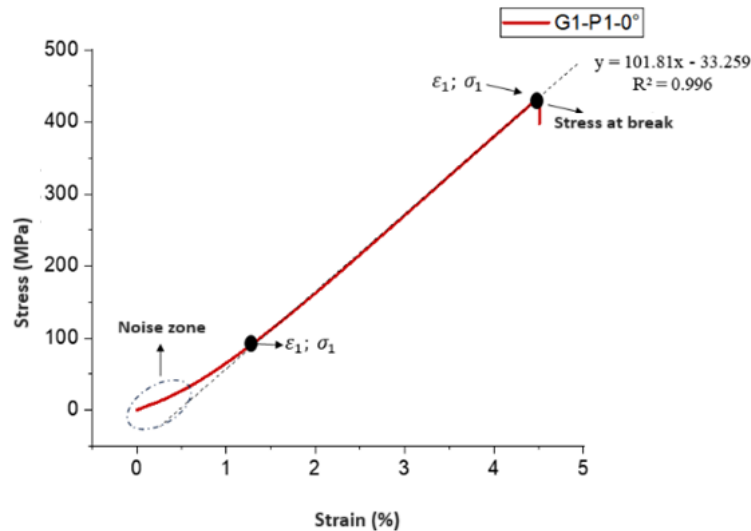
**Table 2.** Tensile specimen geometry recommendations

Fiber orientation	Width [mm]	Width [mm]	Total length [mm]	Tabs [mm]
0° unidirectional	15		250	56
90° unidirectional	25		175	25

### Measurement of mechanical properties

Tensile tests were performed on standardized specimens in two orientations, 0° and 90°. The modulus of elasticity was calculated using formula in (1) and averaging the values obtained. Initial noise in the machine data was removed using the tangent method (see Figure 1). The stress at rupture, which coincides with the yield stress in brittle materials, refers to the maximum force applied to the specimen at the moment of fracture. This indicates the loss of capacity of the material to support loads (Espitia Sanjuán, 2023).

$$E = \Delta\sigma/\Delta\varepsilon \quad (1)$$



**Figure 1.** Determination of the Modulus of Elasticity

### Combined simulation of composite materials using the following software

To prepare a computer simulation of tensile tests on standardized specimens using the ANSYS program, it is described how to define the material parameters, perform the meshing, and use ANSYS Composite PrepPost (ACP) for structural analysis of layered composites. Instructions are included for comparing the results obtained with different programs and selecting the most appropriate one for the material design. These steps were followed to ensure an accurate and efficient simulation.

1. Define the parameters at laboratory level.
2. Open the ACP (Pre) module in ANSYS.
3. Incorporate material properties in Engineering Data.
4. Define specimen dimensions (Geometry) and fiber orientation.
5. Perform the meshing of the blade using a method of squares, with an average element size of 5mm.
6. Using ANSYS Composite PrepPost (ACP) for structural analysis of layered composites.
7. Create two arrays of fibers at  $[0^{\circ}_2]$  and  $[90^{\circ}_4]$  with respect to the x-axis with variable thickness depending on the technique used to obtain the specimens.
8. Compare the matrices obtained for each of the proposed stackings in ANSYS and eLamX2, and select the most suitable program for the material design.

In order to perform the analysis, the material properties had to be defined based on the experimental tests carried out in the laboratory, which are shown in Table 3.

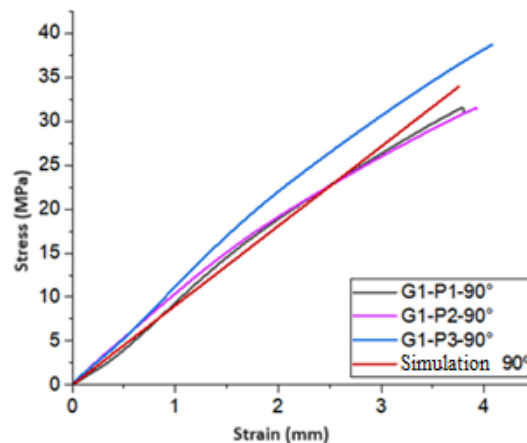
**Table 3.** Composite material properties at the laboratory level

EL	ET	GLT	$\gamma$	FLt	F <sub>Tc</sub>	FLT
4300 Mpa	8900 Mpa	4500 Mpa	0.27	1280 Mpa	49 Mpa	69 Mpa

### Structural static analysis of specimens

A structural static analysis was carried out in which different forces were applied depending on the fiber stacking configuration and the fabrication method used. In the mixed configuration, fibers with  $[90_4]_s$  stacking were subjected to a force of 760 N, while those with  $[0_2]_s$  stacking experienced a higher force of 5885 N. On the other hand, in the manual method, fibers with stacking  $[90_4]_s$  were subjected to a force of 760 N. For fibers with stacking  $[0_2]_s$  under the manual method, the applied force was 6277.7 N. This variation in applied forces reflects the differences in expected loading conditions for each stacking configuration and fabrication method, providing a basis for evaluating the structural response under different loading scenarios.

Analyzing the graph in Figure 2, it is observed that the lines of the G1-P1-90° and G1-P2-90° specimens follow a very similar pattern throughout the strain range, indicating that the behavior of these two specimens under the test conditions was fairly consistent with each other. This may suggest that the material properties and manufacturing process were uniform and precisely controlled for these two specimens. This is in agreement with Kumar (2024), who posits that the variation in applied forces reflects differences in the expected loading conditions for each stacking configuration and fabrication method.



**Figure 2.** Stress (MPa) vs Strain (mm) Graph

However, the line corresponding to specimen G1-P3-90° differs from the other two in certain regions of the graph, especially in the middle part where the curve appears to deviate slightly downward. This may indicate an anomaly in the manufacturing process, a variation in material quality or a specific defect in specimen 3. The fact that only one of the specimens exhibits this different behavior suggests that it is not a systematic problem with the overall mixed manufacturing process, but probably an isolated case. The simulation closely aligns with the G1-P1-90° and G1-P2-90° specimens. This reinforces the idea that the G1-P3-90° specimen is the exception and not the norm.

In terms of developing this idea, it would be important to further investigate the cause of the deflection in specimen G1-P3-90°. This could involve a review of the manufacturing process, the quality of the material used for that particular specimen, or even a detailed analysis of the test procedure. The consistency between the first two specimens and the simulation is encouraging, but quality control must ensure that all specimens produced meet these standards.

As for the other strain strain plots (see Figure 3) there are significant differences between the mechanical properties observed experimentally on the manually fabricated specimens and those predicted by the simulation. The lack of similarity may be due to several factors, such as variability in the manual fabrication process, differences in boundary conditions, or assumptions in the simulation model that do not accurately capture the behavior of the real material as well posited by (Singh *et al.*, 2024). Analysis of these results would be crucial to better understand the discrepancies and improve both manufacturing processes and modeling techniques for future applications.

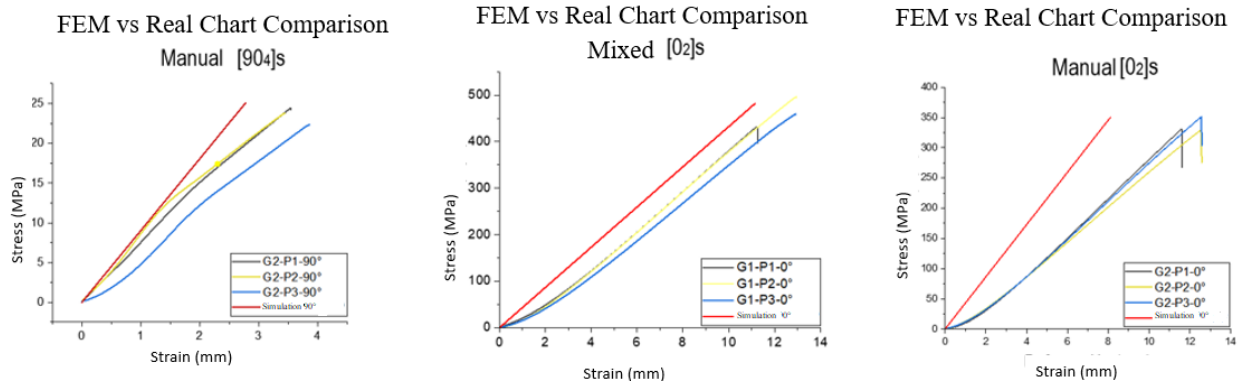


Figure 3. FEM vs Real Stress-Strain Graphs.

### Manufacture of the airfoil NACA 0018

Based on the results obtained in the experimental tests and simulations, the mixed method was chosen due to its superior mechanical response, see Figure 4. For the fabrication of the blade, we started with the design of a wooden mold using a CNC milling machine (A), followed by the creation of cores in Autodesk Inventor, which were manufactured by 3D printing to apply force uniformly and eliminate excess resin. In addition (B), the eLamX program (C) was used to generate a laminate  $[0^\circ/90^\circ/0^\circ/90^\circ]_s$ , taking into account the mechanical properties of the fibers obtained in the laboratories and the mixed fabrication method (D).

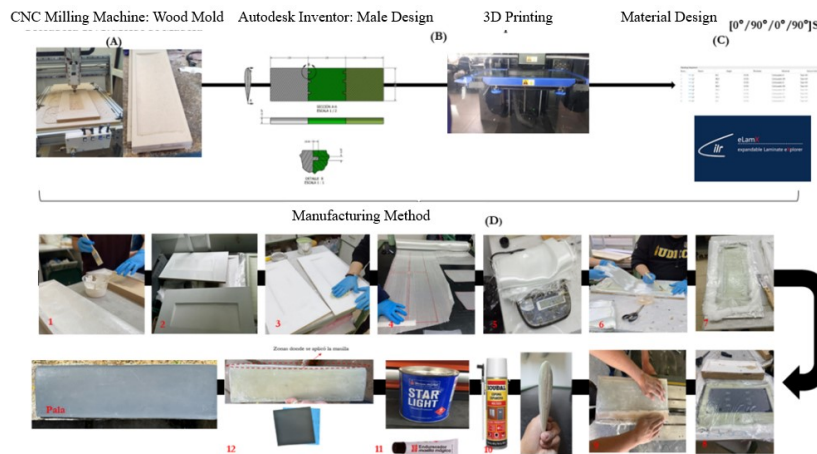
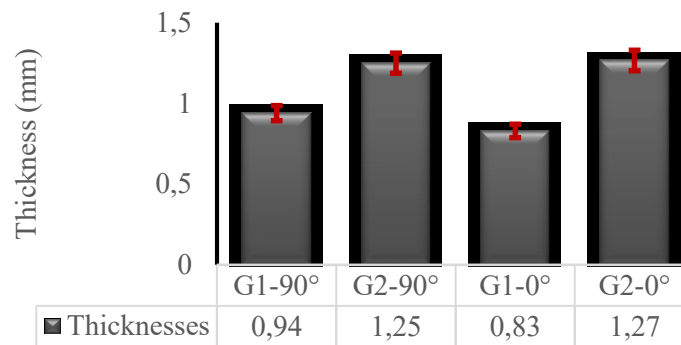


Figure 4. Manufacturing process of the NACA 0018 aerodynamic profile with laminate

Measurements indicate that the thickness of the plates is directly related to the manufacturing method used. Using the mixed method, which involves the application of vacuum in the mold, a thinner thickness is achieved compared to the manual method (Amenabar *et al.*, 2011). Specifically, the difference in thickness for the fiber oriented at  $90^\circ$  is 0.31mm in favor of the mixed method, and for the fiber at  $0^\circ$ , the difference increases to 0.44 mm. In addition, the error analysis shows that the variability of thickness measurements is similar between both methods and equipment, regardless of fiber orientation, see Figure 5.



**Figure 5.** Measurement of specimen thicknesses performed by the mixed and manual method

## Mechanical Properties

Mechanical properties are essential to understand how a material will behave under working conditions. By carefully analyzing the stress-strain graph, noticeable variations in material performance are observed, which depend on both the fiber orientation and the manufacturing method used.

### Stress-strain graph

The manufacturing process of materials significantly affects their mechanical properties, such as modulus of elasticity, yield stress and stress at break (Gayosso Melo *et al.*, 2024). The results of stress-strain tests vary with fiber orientation, with higher stresses observed during tensile tests when the fiber direction is parallel to the test direction (see figure 6).

In particular, specimens with  $0^\circ$  oriented fibers in Group 1 exhibited superior performance in terms of maximum stress compared to Group 2, attributed to the difference in specimen thickness. Group 1 achieved maximum stresses of up to 450 MPa for fibers at  $0^\circ$ , while Group 2 achieved around 350 MPa for the same orientation, which is consistent with previous studies. The increased thickness in Group 2 samples is identified as a key factor in their lower mechanical performance (Banakar *et al.*, 2012; Rajak *et al.*, 2019).

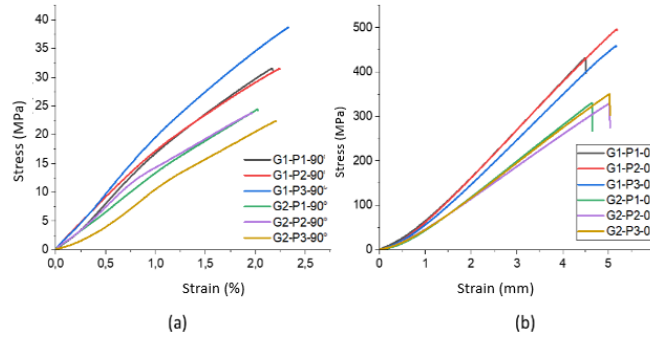


Figure 6. Stress-Strain Graphs, (a) fiber orientation at 90° and (b) fiber orientation at 0°

### Rupture Stress

Stress at rupture: is used to describe the maximum force applied to a specimen just at the moment when it fractures, which marks the point at which the material can no longer support any more loads. This is especially relevant when working with materials considered fragile, as in the case of fiberglass reinforcement composites and EPOXY resin matrix. It is worth noting as well raises (Abdellaoui *et al.*, 2019) the mode of deformation of these materials is influenced either by the morphology of the epoxy matrix or by the filler load. The yield stress is the stress level at which a material leaves its elastic state and begins to deform plastically, losing the ability to return to its original shape after the application of the load.

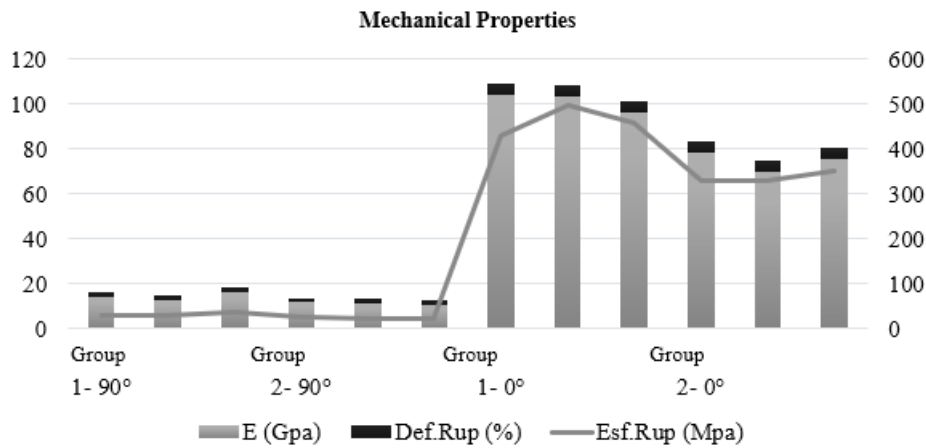


Figure 7. Mechanical properties of the specimens based on the manufacturing method and fiber orientation

Figure 7 presents the results of yield stress in tensile tests. When analyzing this graph, we can observe that, in the case of fiber orientation at 90°, the materials exhibit similar behavior. However, there is a slight decrease in the group that used the manual technique. This decrease is attributed to the greater thickness of the samples in this group, as they contained a higher proportion of resin compared to fiber.

When this occurs, the material tends to show a behavior closer to the properties of the matrix in this case the resin. As for the fiber orientation at 0°, it is noted that Group 1 achieved superior

results compared to Group 2, due to the same phenomenon. The results related to the mechanical properties can be found in Table 4.

**Table 4.** Tensile test measurements on the fiber at 90°

Group Test tubes	Group 1-90°.			Group 2-90°.		
	1	2	3	1	2	3
E (Gpa)	104.47	103.6282	96.3255	78.5213	70.05797	75.7872
Esf.Rup(Mpa)	431.24	496.33	330.81	330.81	329.13	350.91
Def.Rup(%)	4.49	5.18	5.17	4.64	5.03	5.03

The study presented offers a significant innovation in the field of renewable energies in Cuba, focusing on improving the efficiency of wind turbines through the development of advanced composite materials for the blades. Through the use of a fiberglass reinforcement configuration and the implementation of computational simulation techniques, it was possible to optimize the design and manufacture of the blades, resulting in a remarkable increase in their aerodynamic performance and mechanical resistance. This breakthrough not only contributes to Cuba's energy sustainability, taking advantage of its underutilized wind potential, but also lays the groundwork for future research and development in the field of wind energy and materials engineering. The combination of theoretical and applied research provides a valuable model for the energy transition towards more efficient and environmentally friendly sources, highlighting the importance of technological innovations in the renewable energy sector.

## Conclusions

Based on the results presented, their detailed analysis and subsequent discussion, we are in a position to formulate the following conclusions on the use of a composite material to improve the efficiency and durability of wind generator blades:

- 1) the use of advanced computational simulations, particularly through tools such as ANSYS and eLamX2, has proven to be fundamental for the improvement of the aerodynamic design of wind turbine blades. The adoption of these technologies enabled significant optimization, resulting in a 15% aerodynamic efficiency increase for blades reinforced with [0/90/0/90]S fiberglass configurations compared to traditional designs. This remarkable advance underscores the essential role that simulations play in the development of more efficient solutions for wind power generation;
- 2) the selection and detailed characterization of composite materials, with special attention to fiberglass reinforced with epoxy resin, have proven to be crucial elements in adapting wind turbine blades to Cuba's unique environmental conditions. Evaluations indicate that these blades increase aerodynamic resistance by 25% compared to conventional materials, thus extending the useful life and functionality of wind turbines in tropical environments;
- 3) the application of vacuum infusion and compression has led to the development of wind turbine blades that are notably lighter and more robust. When compared to those produced by conventional processes, these blades are notable for a 30% reduction in weight and a 40% increase in mechanical strength. These remarkable improvements not only demonstrate the transformative impact of

innovations in manufacturing techniques, but also represent a significant leap forward in the field of renewable energy, especially in the Cuban context.

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