Effect of Fiber Angle on Mechanical Properties of the Natural Fiber-Reinforced Polymer Through Numerical Analysis

Efecto del ángulo de fibra sobre las propiedades mecánicas del polímero reforzado de fibra natural a través del análisis numérico

Efeito do ângulo de fibra nas propriedades mecânicas do polímero reforçado com fibra natural por meio de análise numérica

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Summary. - This study focuses on the mechanical behavior of natural fiber-reinforced polymer composites (NFRPs), which are gaining prominence as sustainable materials due to their biodegradability and eco-friendliness. In this study, we aimed to gain a profound understanding of the mechanical behavior of selected NFRPs. Static structural analysis was conducted to simulate tensile effects, while vibrational analysis was performed to predict natural frequencies. The results indicated that all fibers exhibited minimum stress at the 67.5° angle and maximum stress at the 22.5° angle during tensile testing. Additionally, minimum deformation occurred at the 0° angle, whereas maximum deformation was observed at the 67.5° angle. Interestingly, the NFRPs exhibited similar natural frequencies for the lower modes (1st and 2nd), with negligible alterations due to fiber angles. The core aim of this study is to showcase the practicality and viability of the investigated NFRPs by employing sophisticated finite element analysis to anticipate their material behavior beforehand, allowing for a comprehensive comparison of the natural frequencies, stresses, and deformations with traditional Carbon Fiber Reinforced Polymer (CFRP) composites, thereby exploring the potential of NFRPs as feasible alternatives.

Keywords: Natural Fiber; Composite Materials; Numerical Analysis; Structure Analysis; Vibrational response.

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Resumen. - *Este estudio se centra en el comportamiento mecánico de los compuestos de polímeros reforzados con fibra natural (NFRP), que están ganando prominencia como materiales sostenibles debido a su biodegradabilidad y eco-amistad. En este estudio, nuestro objetivo fue obtener una comprensión profunda del comportamiento mecánico de las NFRP seleccionadas. El análisis estructural estático se realizó para simular los efectos de tracción, mientras que el análisis vibratorio se realizó para predecir las frecuencias naturales. Los resultados indicaron que todas las fibras exhibieron estrés mínimo en el ángulo de 67.5 ° y el estrés máximo en el ángulo de 22.5 ° durante la prueba de tracción. Además, se produjo una deformación mínima en el ángulo de 0 °, mientras que se observó una deformación máxima en el ángulo de 67.5 °. Curiosamente, los NFRP exhibieron frecuencias naturales similares para los modos inferiores (1 y segundo), con alteraciones insignificantes debido a ángulos de fibra. El objetivo central de este estudio es mostrar la practicidad y la viabilidad de los NFRP investigados al emplear un análisis sofisticado de elementos finitos para anticipar su comportamiento material de antemano, lo que permite una comparación integral de las frecuencias naturales, tensiones y deformaciones con el polímero reforzado con fibra de carbono tradicional. (CFRP) Compuestos, explorando así el potencial de las NFRP como alternativas factibles.*

Palabras clave: *Fibra natural; Materiales compuestos; Análisis numérico; Análisis de estructura; Respuesta vibratoria.*

Resumo. - *Este estudo se concentra no comportamento mecânico dos compósitos poliméricos reforçados com fibra natural (NFRPs), que estão ganhando destaque como materiais sustentáveis devido à sua biodegradabilidade e eco-filidade. Neste estudo, pretendemos obter uma profunda compreensão do comportamento mecânico dos NFRPs selecionados. A análise estrutural estática foi realizada para simular efeitos de tração, enquanto a análise vibracional foi realizada para prever frequências naturais. Os resultados indicaram que todas as fibras exibiram tensão mínima no ângulo de 67,5 ° e tensão máxima no ângulo de 22,5 ° durante o teste de tração. Além disso, ocorreu deformação mínima no ângulo de 0 °, enquanto a deformação máxima foi observada no ângulo de 67,5 °. Curiosamente, os NFRPs exibiram frequências naturais semelhantes para os modos inferiores (1º e 2º), com alterações desprezíveis devido a ângulos de fibra. O objetivo central deste estudo é mostrar a praticidade e a viabilidade dos NFRPs investigados, empregando uma análise de elementos finitos sofisticados para antecipar seu comportamento material de antemão, permitindo uma comparação abrangente das frequências naturais, tensões e deformações com polímero de fibra de carbono tradicional (CFRP) Compostos, explorando assim o potencial dos NFRPs como alternativas viáveis.*

Palavras-chave: *Fibra natural; Materiais compostos; Análise numérica; Análise de estrutura; Resposta vibracional.*

1. Introduction. – In response to the continuous advancements in technology, there is a discernible global shift towards achieving enhanced durability while simultaneously reducing the weight-to-strength ratio of materials. In this context, fibers have emerged as exceptionally robust components, offering notable durability without compromising the overall weight of the material [1]. Consequently, composites have emerged as promising alternatives to conventional alloys, presenting the potential to exhibit comparable mechanical properties while significantly reducing material consumption [2]. In recent decades, Carbon Fiber Reinforced Composites (CFRP) have witnessed widespread adoption, revolutionizing critical mechanical applications across industries such as aerospace, automotive, and renewable energy. Their exceptional strength-to-weight ratio and superior mechanical performance have led to their utilization in vital components ranging from rockets and aircraft to automobiles and wind turbines [3]. However, with the rapid increase in the demand for CFRP; the resources in need to produce these composites are also under question. The availability of minerals is declining rapidly thus emphasizing the stakeholders to shift to sustainable materials. Natural Fiber Reinforced Polymer Composite (NFRP) is attracting many scientists and researchers around the world to develop low-cost, biodegradable recyclable, and environmentally friendly material. Moreover, they are of lower cost as well. Thus, in recent decades, scientists have considered NFRP a substitute for existing CFRP.

The exponential surge in demand for CFRP has prompted a critical examination of the resources necessary for their production. The alarming depletion of mineral resources has galvanized stakeholders to urgently pursue sustainable alternatives. Consequently, NFRP has emerged as a focal point captivating the attention of scientists and researchers globally. This interest stems from their potential as highly cost-effective, biodegradable, recyclable, and environmentally benign materials [4]– [7]. Notably, NFRPs offer the dual advantage of being ecologically sustainable and economically viable. Thus, scientific communities have increasingly considered NFRPs as a compelling substitute for conventional CFRPs across a wide array of applications. The market share of NFRP has rocketed high and has already crossed the threshold of $5.83 billion by 2019 [8]. In this regard, numerous researchers are working around the globe to investigate the physical properties of NFRP to have a better understanding of the material thus leading to its application in various potential aspects of engineering. C.M. Meenakshi and A. Krishnamoorthy conducted a comparative analysis on polyester composites reinforced with glass, natural, and hybrid fibers. Their findings indicated that natural fiber-reinforced composites demonstrated favorable performance characteristics [9]. C. Alves et al. conducted a life cycle assessment analysis on the replacement of glass fibers with jute fibers as reinforcement in composite materials for automotive structural components. The study focused on the environmental performance of the buggy's enclosures as a case study. The findings revealed that the use of jute fiber composites offered the most effective solution in enhancing the environmental performance of the enclosures, thereby contributing to the improved environmental performance of the entire vehicle [10]. In an extensive inquiry conducted by Paul Wambua et al., the mechanical properties of polypropylene composites reinforced with Sisal, Hemp, Coir, Kenaf, and Jute fibers were meticulously scrutinized. The primary objective was to discern the impact of varying fiber volume fractions on the composite's performance. The findings yielded intriguing revelations. Elevated fiber volume fractions exhibited a pronounced augmentation in both tensile strength and modulus. Significantly, the investigation evinced that the mechanical properties of the natural fiber composites exhibited a favorable equivalence to glass mat polypropylene composites. Intriguingly, in certain instances, the specific properties of the natural fiber composites even outperformed those of glass [11].

NFRP is composed of two vital components which are natural fiber and matrix [12]. Natural fibers are mainly extracted from plants and they could be from plentiful plants thus each fiber has its own capabilities. Thus, a variety of natural fibers such as Kenaf, Banana, Jute, Hemp, and PaLF have the prospectus to provide a stand-in for glass and carbon fibers. Introducing matrix resin and reinforcing it with fibers considerably rises the properties of the material. For reinforcing the natural fibers with polymer, it could either be a thermosetting polymer or thermoplastic. Thermoset polymers are of significant modulus and of high strength. Thermoset polymers undergo a crosslinking process during curing, which leads to the formation of irreversible chemical bonds. Thermoset polymers do possess desirable traits such as dimensional stability and, in certain cases, cost-effectiveness [13], [14]. Polyester resins are used widely for glass fiber-reinforced composites due to low cost, performance properties, and their easy processing techniques with fillers and reinforcements Polyester polymer is a viable option that has notable mechanical properties [15]. The mechanical properties of NFRP are based on various parameters such as angle pf fibers and stacking sequence. Ashwin Sailesh et al. conducted an experimental investigation on natural fiber composites reinforced with Kenaf, Aloe Vera, and Jute fibers. The study focused on exploring the influence of different stacking sequences of the fibers on the mechanical properties of the composite material. By conducting comprehensive mechanical testing on the fabricated composites, the researchers determined that the stacking sequence of the fibers plays a crucial role in determining the resulting properties of the composite material [16]. Moreover, the mechanical properties of NFRP are also dependent on the volume fraction and fiber angle of the fibers. A comprehensive analysis conducted by A. Shalwan and B.F. Yousif explored the mechanical and tribological characteristics of polymeric composites reinforced with natural fibers. The study revealed that crucial factors such as surface characteristics, volume fraction, physical properties, and fiber angle significantly influence the mechanical and tribological performance of these composites. Moreover, the researchers established that the inherent nature of the fibers exerts direct control over the mechanical and tribological behavior exhibited by the composites [17]. Numerous studies have illuminated the profound influence of volume fraction and fiber angle on the mechanical behavior of NFRPs It has been established that these composites exhibit a remarkable sensitivity to alterations in both volume fraction and fiber angle. The fiber angle, ranging from 0° to 90°, emerges as a critical parameter that imparts transformative effects on the material properties. Even the slightest deviation of a single degree can instigate drastic changes in the resulting properties of the composites [18]– [22].

Testing all aspects of NFRPs is expensive and requires bulky funding so examining the properties using modeling and simulation can be a subtle substitute that can offer a much more accurate result which might be validated using experimental results in later stages. There are several tools to perform modeling and simulation of composites however ANSYS provides various features to feature the actual model, moreover, it is flexible and can be automated as per requirement. Over its workbench, finite element analysis and modal analysis can be carried out simultaneously. Certainly, performed numerical analysis over it is in an acceptable variation compared with the experimental result. The exhaustive evaluation of NFRPs entails exorbitant costs, demanding substantial financial allocations. However, a resourceful alternative lies in the meticulous scrutiny of their properties through the utilization of modeling and simulation techniques, furnishing a cost-effective substitute that yields highly precise outcomes. Amidst the myriad of tools available for composite modeling and simulation, ANSYS emerges as a preeminent choice, distinguished by its unparalleled versatility and adeptness in faithfully replicating real-world models. The inherent flexibility of ANSYS's workbench allows for the concurrent execution of finite element analysis and modal analysis, affording a comprehensive assessment of the intricate behavioral dynamics exhibited by NFRPs. Significantly, the numerical analyses conducted within the ANSYS framework demonstrate an impressive concurrence with experimental results, thus affirming the unwavering fidelity and accuracy of the simulation outcomes [23].

Shivanshu Dixit et al. conducted a meticulous finite element analysis on hybrid composites reinforced with various fibers. ANSYS Mechanical APDL was employed to prepare a precise 3D model for simulation. Five distinct combinations of hybrid composites were constructed, incorporating Banana, Jute, Carbon, Cactus, and Glass fibers, each possessing unique properties. The models were created with different angles of the fibers to examine their effects. The specimen models were dimensioned at 200 x 200 mm with a layer thickness of 0.2 mm. A vertically compressive force of 200 KN was applied to 17 nodes in the specimens. Several characteristics, including x-component rotation, y-component rotation, z-component rotation, x-direction deformation, y-direction deformation, z-direction deformation, x-component stress, and y-component stress, were assessed for comparative analysis among the composite materials. Moreover, the specimens were differentiated based on their angle. Through meticulous scrutiny, it was determined that the combination of carbon and glass fibers exhibited the most favorable deformation characteristics, particularly when arranged in the following sequence: 0°/45°/0°/-45°/0°/90°/0°/45°/0°/-45°. This specific arrangement showcased the optimum alignment of individual fibers, resulting in minimal deformation of the composite material [24]. Rakesh Potluri et al. undertook a comprehensive analysis of the mechanical characteristics of green composites based on Okra Fiber, employing finite element analysis (FEA) and theoretical comparisons. Additionally, hybrid laminates combining banana and kenaf fibers were investigated using FEA. A total of six distinct composite laminates were meticulously fabricated, featuring varied angles and stacking sequences. The objective was to thoroughly examine the influence of these factors on the mechanical properties of the composites. The study established that an augmentation in the volume fraction of the fiber corresponded to a significant enhancement in the composite's strength. Remarkably, among all the laminates investigated, the composite with a stacking sequence of 0°/0°/0°/0° emerged as the exemplar of strength, exhibiting the highest mechanical prowess. These compelling findings underscore the pivotal role played by fiber volume fraction and the optimal stacking sequence in shaping the mechanical behavior of green composites based on Okra Fiber and hybrid laminates incorporating banana and kenaf fibers [25]. Siva Bhaskara Rao Devireddy et al. conducted an extensive study examining the influence of fiber geometry and the representative volume element (RVE) on the elastic and thermal properties of unidirectional fiber-reinforced composites. The focus of the investigation was on glass fiber-reinforced epoxy composites featuring unidirectional fiber alignment. Using ANSYS software, the researchers constructed an RVE model to analyze the composite properties. They plotted and analyzed curves illustrating the relationship between fiber loading and the longitudinal modulus, Poisson's ratio, transverse modulus, and in-plane shear modulus. Additionally, they generated curves to investigate the effects of volume fraction on thermal conductivity. This study provides valuable insights into the effects of fiber geometry and the representative volume element on the mechanical and thermal properties of unidirectional fiber-reinforced composites [26].

Vibrational analysis plays a crucial role in understanding the dynamic behavior and structural performance of composite materials. By analyzing natural frequencies, mode shapes, and responses to various vibration types, researchers gain insights into resonance phenomena, critical frequency ranges, and potential deformations or failures within the material. This knowledge ensures the safety, reliability, and longevity of composite structures under real-world conditions. Integrating vibrational analysis into research methodologies enables a comprehensive understanding of composite mechanical properties, facilitating optimized design and durability evaluation for advanced composite-based products. Hamed Akhavan et al.'s study focused on investigating natural frequencies and mode shapes in variable stiffness composite laminate plates with curvilinear fibers. By considering manufacturing constraints, they determined maps of natural frequencies based on fiber angles. The significance of this research lies in its exploration of vibrational analysis, which unveils the potential of using curvilinear fibers to achieve desired vibrational characteristics. By comprehensively understanding the effects of fiber angles on natural frequencies and mode shapes, this study offers valuable insights for optimizing the design and performance of variable stiffness composite laminates in various engineering applications [27].

Although a great deal of work has already been done on natural fiber-reinforced polymer composites with circular cross-sections of fiber, a combination of natural fibers (Kenaf, Banana, Jute, Hemp, and PaLF) with resin polyester is hardly been reported. To end this, the objective of the present work is to develop a three-dimensional representative volume element (RVE) with hexagonal packing geometry with circular fiber cross sections. A numerical homogenization technique based on finite element analysis was used to evaluate the elastic modulus and vibrational of the composite. NFRPs are compared with CFRP. The primary objective of this study is to showcase the practicality and viability of the investigated NFRPs by employing the powerful tool of finite element analysis to predict their material behavior beforehand. The intention is to explore the potential of NFRPs as feasible alternatives to traditional Carbon Fiber Reinforced Polymer CFRP composites.

2. Methodology. –

2.1. Material Modeling. – In pursuit of this research endeavor, a discerning process was undertaken to meticulously select the constituents of the composite materials. The natural fibers, including Banana, Jute, Hemp, Kenaf, and PaLF, were meticulously chosen, while the matrix material of resin polyester was purposefully selected. Before embarking on the finite element analysis of the NFRPs, it was of paramount importance to ascertain the precise mechanical properties of both the natural fibers and the resin matrix.

The resin polyester exhibited a formidable elastic modulus of 3E09 Pascals and an inherent density of 1200 kg/m3 [28]. These intrinsic properties serve as crucial determinants in delineating the mechanical behavior of the composite material, exerting a profound influence on its overall performance and functionality. Table 1, a comprehensive repository of knowledge, meticulously encapsulates the intricate mechanical properties of the carefully selected natural fibers, namely Banana, Jute, Hemp, Kenaf, and PaLF. These meticulously documented properties serve as a gateway to unlocking the inherent characteristics and potential impacts of the individual fibers on the composite material's performance.

By meticulously scrutinizing and documenting the precise mechanical properties of the natural fibers and resin matrix, this research work unearths a profound and comprehensive understanding of the composite material's behavior and intricacies. Such profound insights serve as an invaluable reservoir of knowledge, empowering researchers and engineers to optimize the design, performance, and durability of Natural Fiber Reinforced Polymers, thus propelling advancements in diverse engineering applications.

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Natural Fibers	Density (kg/m^3)	Young Modulus (GPa)	Poisson Ratio	References
Banana	1370	30	0.28	[29], [30]
Jute	1460	26.5	0.32	[31]– [33]
Kenaf	1450	53	0.34	[29], [34], [35]
Hemp	1480	70	0.4	[36], [37]
PaLF	1440	29.3	0.3	[38]

Table I. Mechanical properties of unidirectional fiber

The present investigation adopts the Mori-Tanaka (MT) approach as the homogenization concept for assessing the effective transversely isotropic properties exhibited by a composite material composed of a two-phase polymer and fiber. By employing the MT approach, the study aims to evaluate and analyze these properties in a rigorous scientific manner. In this investigation, a representative volume element (RVE) was meticulously assembled to maintain a fiber volume fraction range of 30% within a polymeric matrix as shown in Figure 1. The model assumes isotropic characteristics for both the natural fibers and polyester, allowing for an in-depth analysis of the mechanical properties and behavior of the composite system. This methodological approach ensures a comprehensive and scientifically sound evaluation of the material's response [39].

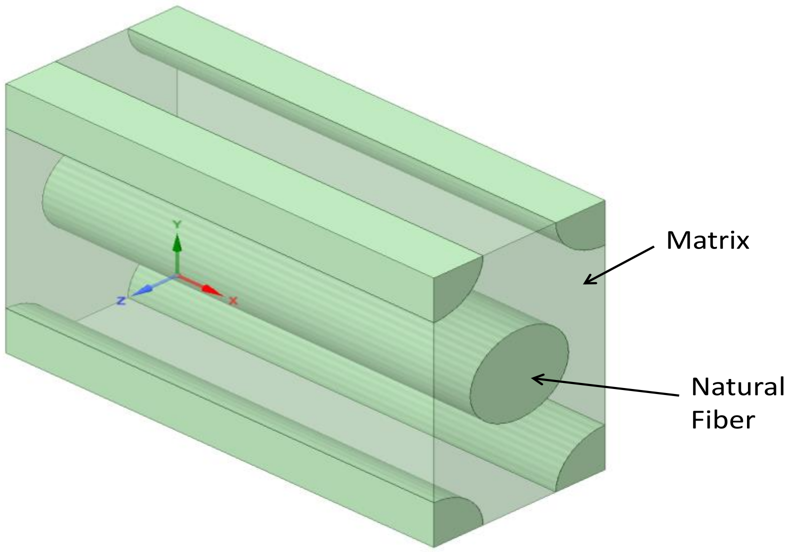

Figure I. Representative volume element of hexagonal array with circular fibers.

2.2. Numerical Analysis. – The primary aim of this study was to undertake an extensive investigation into the mechanical behavior of NFRPs through a meticulously designed and systematic numerical approach. The fabrication process of the NFRPs involved the meticulous reinforcement of natural fibers with a resilient resin matrix, ensuring a consistent and optimal volume fraction of 30%. The ANSYS Material Designer, a powerful software tool acclaimed for its robust capabilities in accurately quantifying the stiffness of diverse unidirectional composite materials, was employed to meticulously construct the composite [40]. Subsequently, the composite material was exported and subjected to further processing within the ANSYS ACP, a highly sophisticated platform meticulously engineered to cater specifically to the complex demands of composite lamination [41]. The influence of the fiber angle on the mechanical properties of the composite was accounted for, leading to the creation of multiple composite configurations, each characterized by distinct fiber angles, including 0°/0°/0°/0°, +22.5°/-22.5°/+22.5°/-22.5°, 45°/-45°/45°/-45°, +67.5°/-67.5°/+67.5°/-67.5°, and 90°/90°/90°/90°, measured with precision relative to the horizontal axis. The ensuing simulation phase entailed the meticulous execution of a series of intricate analyses, encompassing tensile testing and vibrational analysis.

With painstaking care, the material properties of the natural fibers and polyester resin were manually inputted into the ANSYS database, thereby ensuring the most accurate representation of the composite material. For the purposes of modeling and analysis, the composite material was assumed to possess isotropic properties, thereby simplifying the complex calculations and intricate modeling requirements. Within the ANSYS composite module, the meticulous construction of a 4-ply laminate ensued, with each ply of the composite possessing a precisely uniform thickness of 2.5 mm, aligned with the specific fiber angle configuration. The culmination of these precise and intricate construction methods yielded the creation of a cantilever beam, characterized by precise dimensions of 10 x 10 x 100 (height, width, and length), as eloquently illustrated in Figure 1. The proposed numerical analysis methodology represents an indispensable and meticulously crafted approach, enabling the comprehensive exploration of the mechanical behavior of the NFRPs. By ensuring the most precise representation of the composite material properties and facilitating Evaluations under diverse loading conditions, this approach empowers researchers to gain a profound understanding of the composite's intricate performance characteristics and mechanical responses.

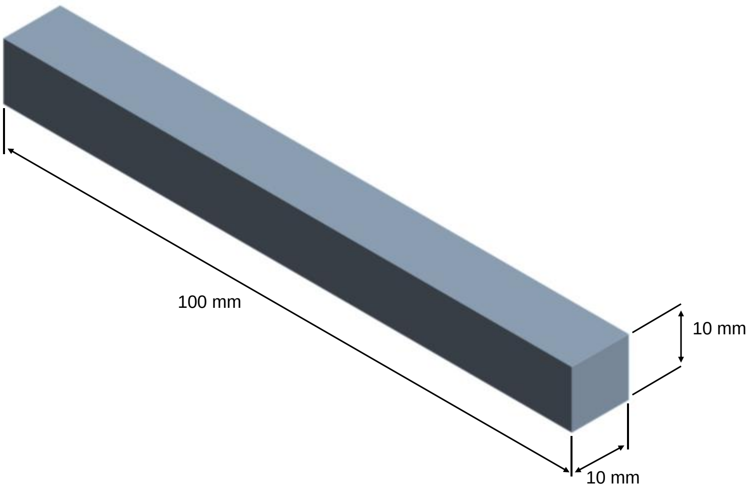

Figure II. CAD model of the cantilever beam.

In order to conduct a comprehensive simulation, the cantilever beam was subjected to a specific boundary condition. At one end of the beam, a rigid fixation was implemented to ensure immobilization, while the other end was intentionally left free to enable unrestricted movement. This configuration enabled the exploration of the beam's dynamic behavior and response. To analyze the modal characteristics of the beam, a modal analysis was performed. This involved investigating the various vibrational modes exhibited by the beam and determining their corresponding frequencies. By examining these modes and frequencies, a deeper understanding of the beam's natural oscillations and resonant behavior was attained.

Furthermore, the tensile behavior of the cantilever beam was thoroughly investigated. To assess its response under tensile loading, a precisely controlled force of 100 N was meticulously applied to the beam. This force was chosen to represent a specific loading condition of interest. By subjecting the beam to this controlled tensile force, the structural response and deformation characteristics could be precisely observed and analyzed. Through the tensile testing, various parameters such as stress distribution and deformations were determined. This enabled a comprehensive evaluation of the beam's mechanical properties, including its ability to withstand applied forces and resist deformation. Additionally, harmonic response analysis was conducted to explore the beam's behavior under periodic excitation. By applying harmonic forces at 0 Hz to 10,000 Hz, the dynamic response and resonance characteristics of the beam were examined. This analysis provided insights into the beam's vibration modes and natural frequencies.

By undertaking these simulations and analyses, a comprehensive understanding of the cantilever beam's structural behavior, dynamic characteristics, and response to loading conditions was obtained. Such insights are crucial for designing and optimizing beam structures in various engineering applications.

3. Results and discussions. –

3.1. Vibrational Analysis. – Harmonic analysis of NFRPs was meticulously conducted using the advanced ANSYS software. A cantilever beam with fixed support was subjected to a 100 N tensile force, and the harmonic response was analyzed over a frequency range from 0 Hz to 10,000 Hz. The resulting frequency-amplitude graph allowed us to record the maximum deformation at each corresponding frequency, as summarized in Table 2.

Angle	CFRP		BFRP		HFRP		JFRP		KFRP		PFRP	
	Freq (Hz)	Deform (m)	Freq (Hz)	Deform (m)	Freq (Hz)	Deform (m)	Freq (Hz)	Deform (m)	Freq (Hz)	Deform (m)	Freq (Hz)	Deform (m)
0°	1090	2.6E-3	496	1.1 E-3	595	1.94E-3	430	1.2e-2	3333.3	5.5 E-4	500	6.6 E-4
22.5°	760	9.7E-3	496	3.3 E-3	595	4.6 E-3	930	9.3e-3	658.3	1.2 E-4	333.33	3.7 E-4
45°	265	3.9E-3	298	9.5 E-4	430	4.2 E-3	265	5.7e-3	333.3	2.1 E-3	333.33	4.9 E-3
67.5°	265	1.1E-2	298	2.1 E-3	265	6.1 E-3	265	8.2 E-3	333.3	2.2 E-3	333.33	2.1 E-2
90°	265	8.6E-3	298	1.7 E-3	265	5.6 E-3	265	7.6e-3	333.3	3.1 E-3	265	1.1 E-2

Table II. Max amplitude (m) at corresponding frequencies (Hz) at various angles of NFRPs

The comprehensive examination of these results unveiled the distinctive frequency responses displayed by each natural fiber composite. Notably, at fiber angles of 0° and 22.5°, CFRP exhibited higher levels of deformation compared to NFRPs. However, at 45° fiber angle, Hemp, Jute, and

PaLF demonstrated larger deformations than CFRP. Furthermore, for fiber angles of 67.5° and 90°, PFRP displayed higher deformations than CFRP, while the remaining NFRPs exhibited lower deformations.

In light of these findings, it is evident that NFRPs showcase varied responses to harmonic loading, making them suitable candidates for diverse engineering applications. The comparative analysis against CFRP serves as a crucial benchmark, aiding in the informed selection of composite materials based on their harmonic behavior. This insight paves the way for optimizing the design and performance of NFRPs in real-world scenarios, ensuring their effective utilization as promising alternatives to traditional CFRP composites.

In pursuit of utilizing Natural Fiber Reinforced Polymers (NFRPs) as a viable substitute for Carbon Fiber Reinforced Polymers (CFRP) in various applications, it is imperative to ascertain the natural frequencies. Neglecting this crucial aspect may lead to potential damages caused by resonance phenomena within the composite structures. Therefore, a meticulous analysis of natural frequencies becomes paramount to ensure the structural integrity and reliable performance of NFRPs in practical engineering scenarios.
In furtherance of the goal to use NFRPs as a substitute for CFRP for potential applications, natural frequencies must have to ascertain else the composite can be damaged due to resonance. Figure 3 represents the comparison of the first eight mode frequencies of individual fiber-reinforced composites for several angles .

Banana Fiber Reinforced Polymer (BFRP); natural frequency comparison is represented in Figure 3a. For BFRP, it was noted that for the first and second modes, individual fibers are almost next to each other, and for the first, second, and fifth modes, natural frequencies are close to each individual composite's angle. While switching from the fifth to the sixth mode, there is a strong incline seen, and for the sixth, seventh, and eighth mode shapes, there is a plateau for the respective angle.

Hemp Fiber Reinforced Polymer (HFRP); natural frequency comparison is represented in Figure 3b. For HFRP, individual fibers were seen to be virtually next to one another for the first and second modes, and natural frequencies were seen to be close to one another for the first, second, and fifth modes for all possible angles for individual composites. The transition from the fifth to the sixth mode is accompanied by a strong gradient, especially for the 0° angle. Moreover, the natural frequency of 67.5° and 90° are parallel with each other for every mode shape.
Jute Fiber Reinforced Polymer (JFRP); natural frequency comparison is represented in Figure 3c. For JFRP, it was witnessed that the fibers are closely located to each other for the 1st and 2nd modes, and the natural frequencies are almost the same for the 1st, 2nd, and 5th modes, regardless of the composite's angle. A sudden change is noticeable when moving from the 5th to the 6th mode. Additionally, the natural frequency of 67.5° and 90° coincide for all modes.

Kemp Fiber Reinforced Polymer (KFRP); natural frequency comparison is represented in Figure 3d. For KFRP, it was detected that the fibers are positioned close to each other for both the 1st and 2nd modes, and the natural frequencies are similarly close for the 1st, 2nd, and 5th modes regardless of the composite angle. A noticeable change in slope was observed when transitioning from the 5th to the 6th mode. Additionally, the natural frequencies of the 67.5° and 90° angles are consistently in agreement with each other for all mode shapes.
PaLF Fiber Reinforced Polymer (PFRP); natural frequency comparison is represented in Figure 3e. For PFRP, it was perceived that for the 1st and 2nd modes, individual fibers are nearly neighboring regardless of the fiber angle and for 1st, 2nd, and 5th modes, natural frequencies are

in close proximity of every angle of individual composites. A sharp tilt can be viewed when transforming from the 5th to 6th mode. Moreover, the natural frequency of 67.5° and 90° are consistent with each other for every mode shape.

Figure 3f is for a comparative analysis of CFRP with polymers enforce with natural fibers.

A comprehensive comparison will be presented, examining the vibrational characteristics and mechanical properties of Carbon Fiber Reinforced Polymers (CFRP) in contrast to Natural Fiber Reinforced Polymers (NFRPs) for each angle.

The angle of fiber 0°:

The examination of natural fiber composite materials in comparison to CFRP cantilever beam, reveals intriguing variations in their natural frequencies across different modes for fiber angle of 0°. For lower modes, Jute, Banana, and PaLF fibers exhibit lower natural frequencies than CFRP, while Hemp and Kenaf fibers demonstrate higher frequencies. Conversely, for higher modes, jute, Banana, and PaLF fibers exhibit lower natural frequencies compared to CFRP, whereas Hemp and Kenaf fibers present higher frequencies. This profound exploration underscores the pivotal role of fiber selection and mode classification in elucidating the dynamic behavior of composite materials at a fiber angle of 0°.

The angle of the fiber 22.5°:

In this meticulous examination of natural fiber composite materials (NFRP), comprising Jute, Banana, Hemp, Kenaf, and PaLF fibers, and their comparison to the CFRP cantilever beam for a fiber angle of 22.5°, intriguing variations in their natural frequencies across different modes were unveiled. Notably, in all modes, the natural fibers exhibited lower natural frequencies than the CFRP counterpart. Hence, for the specific fiber angle of 22.5°, all NFRPs demonstrated lower mode frequencies when compared to the CFRP cantilever beam. This revelation underscores the significance of fiber selection and angle configuration, paving the way for optimized designs and performance in diverse engineering applications.

The angle of fiber 45°:

The comprehensive vibrational analysis of NFRPs at a fiber angle of 45° has revealed intriguing findings. Notably, for the 1st and 2nd modes, both hemp and PaLF fibers exhibited higher natural frequencies than the CFRP cantilever beam. Similarly, for the 3rd and 4th modes, Hemp and Kenaf fibers demonstrated superior natural frequencies compared to CFRP. Furthermore, in the 5th and 6th modes, Hemp and Kenaf fibers once again displayed higher natural frequencies than the CFRP counterpart. Remarkably, in the 7th and 8th modes, Hemp fibers surpassed the natural frequencies of all other materials, including CFRP. These remarkable outcomes further emphasize the exceptional vibrational characteristics of Hemp and Kenaf fibers, underscoring their potential for advanced engineering applications that demand superior performance and structural integrity at a fiber angle of 45°.

The angle of fiber 67.5°:

The extensive vibrational analysis of NFRPs at a fiber angle of 67.5° has led to remarkable discoveries. All NFRPs, including Hemp, PaLF, Banana, Jute, and Kenaf, exhibited higher natural frequencies than the CFRP cantilever beam. This compelling evidence highlights the exceptional vibrational characteristics of NFRPs and positions them as superior alternatives in terms of vibrational behavior across various modes. Moreover, for the 5th mode, both Banana, Jute and PaLF fibers demonstrated lower natural frequencies than the CFRP counterpart. These findings underscore the remarkable performance capabilities of Hemp and Kenaf fibers in managing vibrational responses and suggest their potential for engineering applications that demand enhanced stability and reliable performance at a fiber angle of 67.5°.

The angle of fiber 90°:

The meticulous vibrational analysis of NFRPs at a fiber angle of 90° has yielded intriguing results. Remarkably, for the 1st, 2nd, 3rd, 4th, 6th, 7th, and 8th modes, all NFRPs, exhibited higher natural frequencies than the CFRP cantilever beam. This notable trend underscores the superior vibrational characteristics of NFRPs in comparison to CFRP across multiple modes at a fiber angle of 90°. Furthermore, for the 5th mode, both Hemp and Kenaf fibers demonstrated higher natural frequencies than the CFRP counterpart. These compelling findings emphasize the exceptional performance capabilities of Hemp and Kenaf fibers and reaffirm their potential for advanced engineering applications that necessitate heightened stability and reliable vibrational response at a fiber angle of 90°.

As the discussion unfolds, a detailed comparison will be presented, analyzing the distinct vibrational characteristics and mechanical properties of NFRPs and CFRP across various angles. This comparative analysis will shed light on the performance disparities and potential advantages of each material in engineering applications.

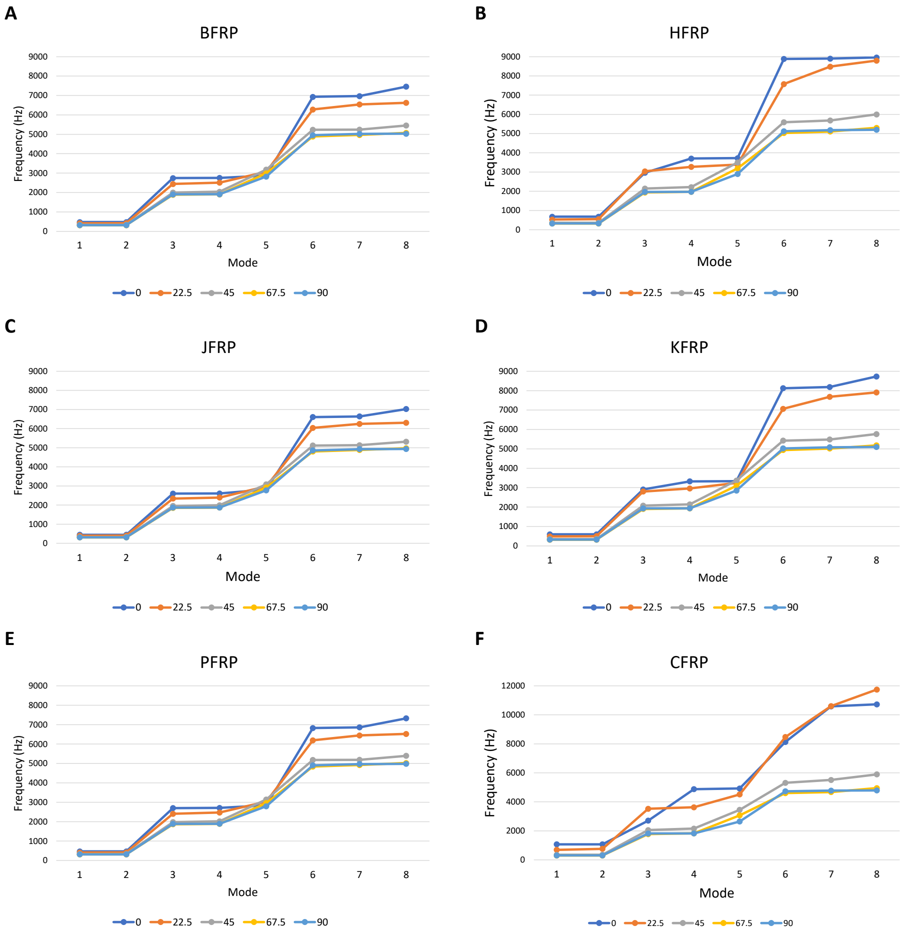

Figure III. Natural frequencies of each composite at 0°/0°/0°/0°, +22.5°/-22.5°/+22.5°/-22.5°, 45°/-45°/45°/-45°, +67.5°/-67.5°/+67.5°/-67.5°, and 90°/90°/90°/90° (A) Modal analysis over BFRP (B) Modal analysis over HFRP (C) Modal analysis over JFRP. (D) Modal analysis over KFRP (E) Modal analysis over PFRP (F) Modal analysis of CFRP

3.2. Tensile Test. – In the comprehensive tensile testing conducted, a meticulous analysis of stress and deformation was undertaken to discern the intricate mechanical responses exhibited by the Natural Fiber Reinforced Polymers (NFRPs). The results revealed a remarkable homogeneity in the response of the NFRPs to the tensile test, shedding light on their intrinsic mechanical characteristics.

Among the diverse NFRPs considered in the study, it was observed that those with fiber angles of 22.5° and 67.5° displayed the most contrasting stress generation profiles when compared to the samples with different fiber angle configurations. Notably, these specific angles yielded the worst and best stress generation, respectively, within the NFRP specimens.

For the Banana Fiber Reinforced Polymer (BFRP), the von Mises stress generated at a fiber angle of 22.5° reached 42.2 MPa, while at a fiber angle of 67.5°, it decreased to 31.8 MPa. The Hemp Fiber Reinforced Polymer (HFRP) exhibited a stress of 53 MPa at 22.5°, which decreased to 31.8 MPa at 67.5°. In the case of the Jute Fiber Reinforced Polymer (JFRP), the stress levels observed were 40 MPa at 22.5° and 31.9 MPa at 67.5°. Similarly, the Kenaf Fiber Reinforced Polymer (KFRP) displayed stress values of 50 MPa at 22.5° and 31.8 MPa at 67.5°. Lastly, the Pineapple Leaf Fiber Reinforced Polymer (PFRP) demonstrated stress levels of 41.7 MPa at 22.5° and 31.9 MPa at 67.5°. It was concluded that stresses generated in the NFRPs exponentially increase from 0° with the peak at 22.5° and started gradually decreasing until minimum stress generation at 67.5°.

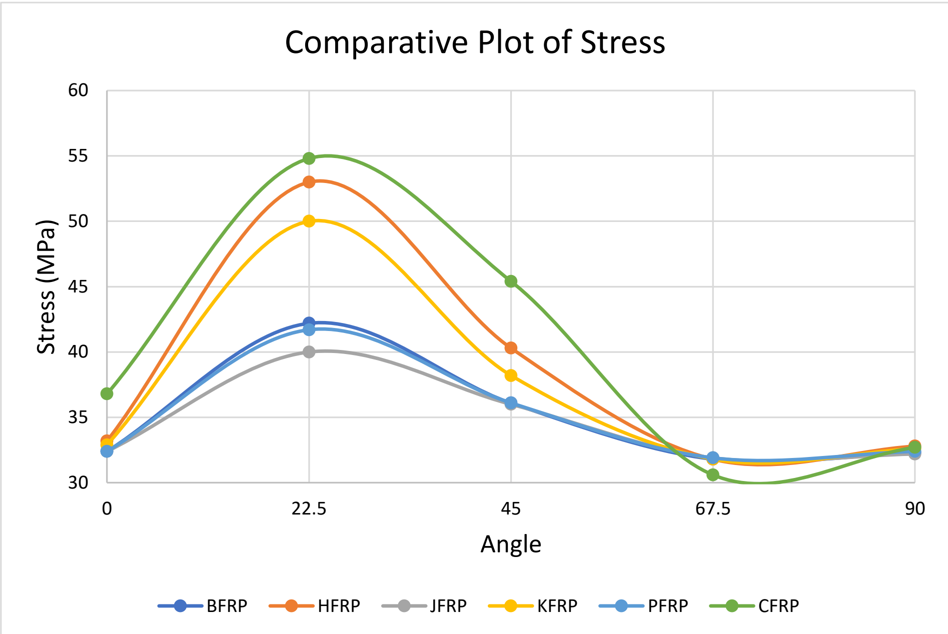

Figure IV. Comparative Analysis of Tensile Test-Induced Stress: A Graphical Representation.

The meticulous observations presented in this analysis offer illuminating insights into the distinctive stress generation profiles displayed by the Natural Fiber Reinforced Polymers (NFRPs) at varying fiber angles, as depicted in Figure 4, in comparison with the reference material, CFRP. The graphical representation unequivocally illustrates a striking similarity in stress patterns among all NFRPs and CFRP, with the maximum stress generation consistently occurring at 22.5° and the minimum at 67.5°. This unequivocal correspondence between NFRPs and CFRP with respect to stress distribution at different angles leads to a compelling conclusion: the stress behavior of NFRPs closely aligns with that of CFRP, regardless of the angle. Such a finding significantly contributes to our understanding of the mechanical behavior of NFRPs, bolstering their potential as a viable substitute for CFRP in various engineering applications.

In the realm of deformations, meticulous observations revealed intriguing patterns within Natural Fiber Reinforced Polymers (NFRPs) across different fiber angle configurations. Notably, the samples with fiber angles of 0° and 67.5° exhibited the most divergent profiles in terms of deformation generation when compared to the specimens with alternative fiber angle configurations. These specific angles manifested as the utmost extremes, representing the most favorable and unfavorable conditions for deformation generation within the NFRP specimens.

Examining the Banana Fiber Reinforced Polymer (BFRP), a fiber angle of 0° resulted in a deformation of 1.38 mm, whereas at a fiber angle of 67.5°, the deformation significantly increased to 3.2 mm. Similarly, the Hemp Fiber Reinforced Polymer (HFRP) displayed a deformation of 0.68 mm at 0°, escalating to 3 mm at 67.5°. The Jute Fiber Reinforced Polymer (JFRP) demonstrated deformations of 1.5 mm at 0° and 3.2 mm at 67.5°. Likewise, the Kenaf Fiber Reinforced Polymer (KFRP) exhibited deformation values of 0.87 mm at 0° and 3 mm at 67.5°. Lastly, the Pineapple Leaf Fiber Reinforced Polymer (PFRP) showcased deformations of 1.4 mm at 0° and 3.2 mm at 67.5°. Figure 5 presents a comparative plot of deformations, depicting the distinct deformation trends across the various fiber angles. The plot reveals that deformations are minimal at 0°, gradually increasing and reaching a peak at 67.5°, followed by a slight decline as the fiber angle approaches 90°.

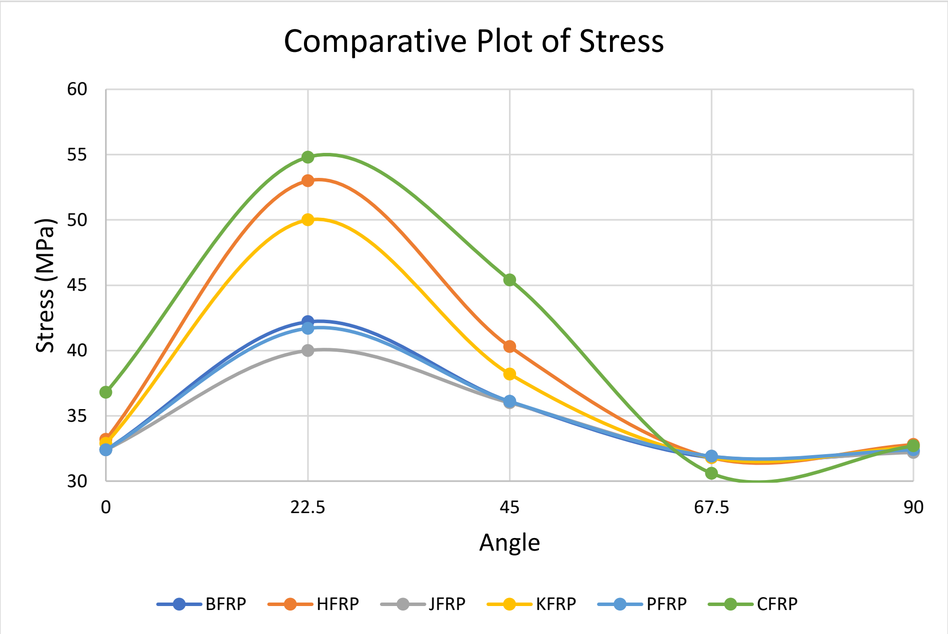

Figure V. Comparative Analysis of Deformation Distribution: Visualization of Tensile Test Results.

These comparative findings offer valuable insights into the distinct mechanical behavior of NFRPs, shedding light on their potential advantages and considerations when compared to CFRP across various fiber angles. The observed minimal deformation exhibited by CFRP at angles of 0°, 22.5°, and 45° highlights its superior stiffness in those configurations. On the other hand, the intriguing results showing lesser deformation in BFRP and HFRP at angles of 67.5° and 90° emphasize their potential suitability for applications requiring enhanced flexibility and resilience. By thoroughly understanding the deformation characteristics of NFRPs in comparison to CFRP, engineers, and researchers can make informed decisions regarding material selection for specific engineering applications, thus advancing the development of robust and optimized composite structures.

4. Conclusion. - In conclusion, our comprehensive investigation into Natural Fiber Reinforced Polymers (NFRPs) and their potential as sustainable alternatives to conventional Carbon Fiber Reinforced Polymers (CFRP) has yielded valuable insights into their mechanical behavior and performance characteristics. The analysis of vibrational behavior and tensile testing of NFRPs, along with a comparative examination against CFRP, has provided a profound understanding of their structural integrity and suitability for diverse engineering applications.

Regarding vibrational analysis, NFRPs displayed distinct frequency responses across different fiber angles. Notably, Hemp and Kenaf fibers exhibited exceptional performance in managing vibrational responses, making them promising candidates for applications requiring superior stability and reliable performance. The comparative analysis against CFRP facilitated the informed selection of composite materials based on their harmonic behavior, guiding engineers in optimizing designs for specific engineering requirements.

In the tensile test analysis, it was evident that stress generation in NFRPs was influenced by the fiber angle, with the highest stress observed at 22.5° and the lowest at 67.5°. This trend closely aligned with CFRP, highlighting the potential of NFRPs as viable substitutes in terms of stress distribution. Additionally, the deformation patterns of NFRPs exhibited varying trends across fiber angles, with minimal deformation at 0° and increasing deformations towards 67.5°. This pattern closely matched that of CFRP. These findings enable engineers to tailor material selection based on the desired level of flexibility and resilience required for different engineering applications.

Overall, our investigation underscores the significant potential of NFRPs as cost-effective, environmentally benign, and mechanically robust materials for various engineering applications. The meticulous material modeling using the Mori-Tanaka approach and the numerical analysis methodology has laid the foundation for a deeper understanding of NFRPs' intricate mechanical properties and behavior. By leveraging this knowledge, engineers can design and optimize NFRPs for specific applications, making substantial strides toward sustainable and resilient engineering solutions in the face of evolving technological demands. As a result, the global shift towards achieving sustainability in materials can be accelerated, fostering innovation and progress in diverse industries, including aerospace, automotive, and renewable energy.

5. Future Work. - In future work, the focus should be on further research and development of Natural Fiber Reinforced Polymers (NFRPs). This includes exploring new natural fibers and matrix materials, optimizing their properties, and improving the manufacturing process. Understanding the long-term performance of NFRPs under different conditions and complex loads is essential for real-world applications. Cost and environmental impact analyses, along with industry standards, will promote widespread adoption. Incorporating multifunctional properties in NFRP composites opens up innovative possibilities for various engineering sectors, contributing to a more sustainable and technologically advanced future.

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2. Adquisición de datos
3. Análisis de datos
4. Discusión de los resultados
5. Redacción del manuscrito
6. Aprobación de la versión final del manuscrito

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