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Natural-Fibre-Reinforced Composite-Based Micro-Size Wind Turbines: Numerical Analysis and Feasibility Study

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Abstract: Due to their inherent advantages, micro-sized horizontal axis wind turbines (HAWT) are preferred over vertical axis wind turbines (VAWT) for urban applications. Typically, HAWTs on the market are constructed using steel, alloys, or fibre-reinforced composites, with the latter being the most economical and stable in comparison to steel and alloy-based HAWTs. Nevertheless, in light of the increased emphasis on cost savings and environmental sustainability, natural-fibre composites have become more desirable. This study focuses on the implementation of flax-fibre-reinforced HAWT wind blades designed for urban applications in particular. The proposed wind blades were designed using CATIA and their feasibility and performance were evaluated via numerical analyses in ANSYS. Structural, modal, and harmonic analyses were conducted under various loading conditions. The results indicate that flax-fibre-reinforced wind blades possess higher natural frequencies, greater stability, and lower deflection amplitudes at resonance frequencies than other materials.

Keywords: horizontal axis wind turbines; flax-fibre-reinforced composites; CATIA; ANSYS; numerical analysis; natural frequency; composite materials; natural fibre

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1. Introduction

Renewable energy has gained significant traction in the energy mix with its development encouraged by government policies across the globe. Wind energy has become a vital part of the renewable energy sector, and is the second-largest standalone renewable energy-producing technology in the world, falling behind hydro-power. As of the September 2022 report by the International Energy Agency (IEA), renewable electricity approximately makes up 29% of the world's total electricity production, where wind accounts for 23.5% of the renewable sources, making it 6.8% of the total electricity production; the statistics by source are visually represented in Figure 1 [1]. The largest producers of wind by order of country are China, the United States, Germany, Brazil, and India; Figure 2 shows the wind generation capacities of countries across the globe [2]. Wind production plants are broadly classified as onshore and offshore, where onshore, as the name suggests, refers to the turbines installed on land as opposed to offshore where the turbines are installed in bodies of water, typically in the sea. China continues to be the leader in not only the production of wind energy but also in its expansion with the highest onshore and offshore installations every year [3]. Globally, onshore installations are dominant compared to offshore installations, with onshore wind turbines accounting for 93.2% of the total capacity as of 2021 [1]. The growth in the installation of wind turbines saw the most significant bump in 2021 with a 17% increase in the total capacity which is a 55% increase in the growth compared to preceding years [1]. Various countries have set net-zero targets to reduce carbon dioxide and greenhouse gas emissions based on their respective timelines and this progress marks a positive start toward achieving those goals [4]. However, considering the earliest target, which is 2030, the progress is inadequate to meet the expected wind capacity to fulfil such targets [3]. The past, current, target capacities, and predicted capacities based on the reports and with respect to the current capacity growth rate are illustrated in Figure 3 [1,3].

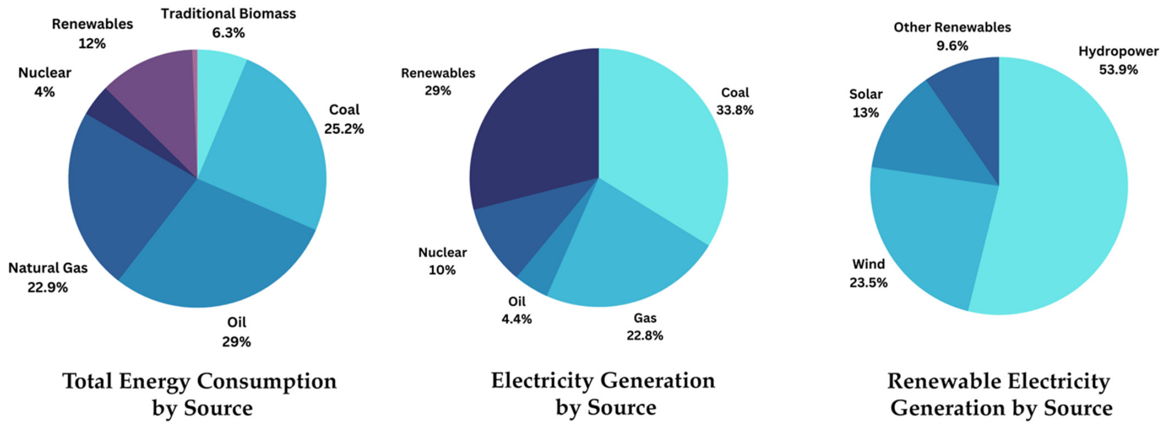

Figure 1. Global energy statistics.

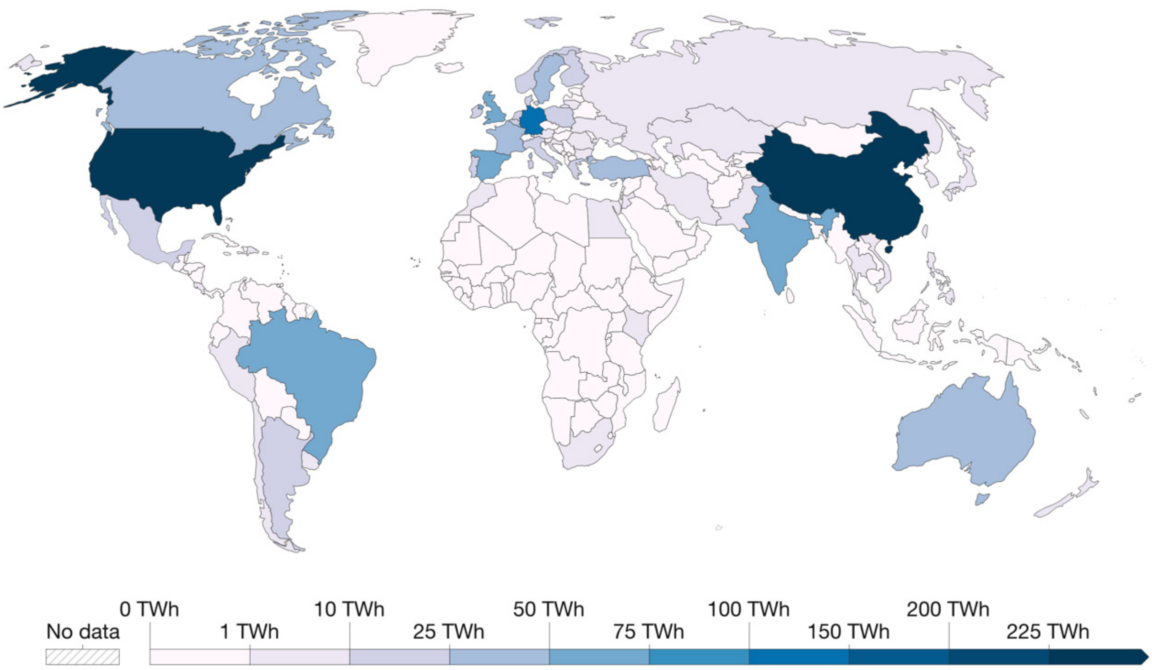

Figure 2. Wind power generation capacity by country, 2022.

Wind turbines were first built in the early 19th century, but it was not until the 1970s that they were developed for commercial use [5,6]. Since then, the technology has improved significantly and has become more efficient and more commercially viable. Six major areas where the wind energy sector faces both short- and long-term challenges include system, society, supply chain, technology, infrastructure, and workforce [7–11]. The system refers to the way each country promotes and adopts the technology with the necessary policies and incentives, which is considered crucial since it creates a favourable environment for investors. Public awareness and social acceptance of technology play a crucial role and are factors that come under the area of society. Supply chain refers to the rise of a local market for technology with players emerging to provide materials, manufacturing, and transportation for the technology's implementation. Infrastructure for its operation is important for its easy adoption, particularly with respect to the grid. Skilled labour and workforce are another special concern in this field. Finally, although the existing technologies make wind-energy generation viable, it is important to invest in research and development to ensure that the sector can meet future demands, especially considering the net zero roadmaps. Some of the various aspects where the technology needs improvement include composite materials, additive manufacturing of blades, the ability for onsite assembly, higher efficiency, and better energy storage technologies.

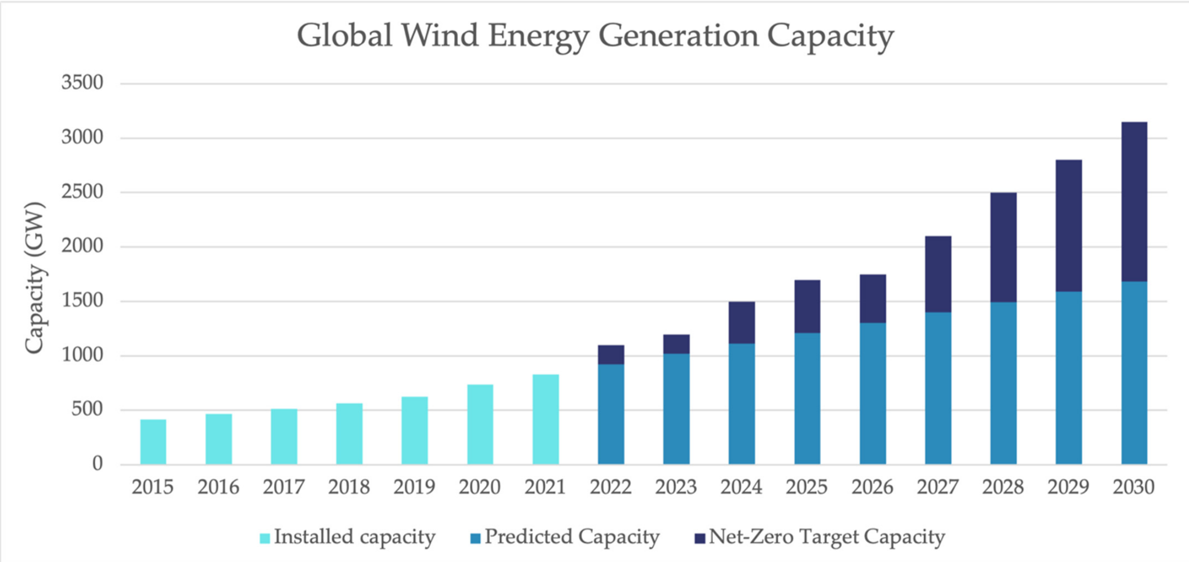

Figure 3. Global wind energy capacity.

During the initial stages, one of the first installed wind turbines collapsed after only a few hundred hours of non-periodic operation [12]. This illustrated early on the effect that metals had on turbines and how critical the choice of materials was in this field of technology. The first reasonably efficient three-blade wind turbine was the Gedser wind turbine developed between 1956–1957 by Johannes Juul [13]. The structure was robust, composed of steel spars, aluminium shells, and wooden ribs which turned out to be a reasonable success that operated for 11 years without maintenance [14,15]. This outright proved the crucial role played by the choice of materials. To lower production costs, improve power generation stability, and reduce weight, wind turbine blades began to be manufactured predominantly of composite materials after the 1970s [6,16,17]. Recent times have seen researchers showing interest in adopting natural-fibre composites for various applications considering their biodegradable and eco-friendly nature [18,19]. The work put forth in the paper focuses on utilising flax fibre for the design of micro-sized HAWTs, suitable for offshore installations, particularly for urban applications.

The variation in the fibre volume fraction is a highly influential factor that determines the mechanical properties of the fibre-reinforced composite materials [20]. On the frontiers of research, various studies have been conducted to evaluate the mechanical properties of these composites with different fibre volume fractions [21]. Current manufacturing processes prefer to use carbon-glass fibres, as well as thermoset polymers, owing to their superior strength [22]. However, the waste disposal of such blades is an increasingly pressing issue in today's world, considering their non-recyclable nature. Landfills are no longer a viable option due to the high organic content of the blades, which is detrimental to the environment, making it necessary to establish alternative end-of-life methods [23]. An evident solution, as suggested by the study, is to utilise natural-fibre materials with recyclable thermoplastic resin for the design of the blades which could facilitate a closed-loop system where materials from old blades could be recycled into new ones [24]. Natural fibres are biodegradable in nature, which makes them eco-friendly and offers reasonable mechanical properties, light weight, lower cost, and ease of fabrication [25,26]. There are numerous studies in the past that have used natural-fibre-based composites to manufacture wind turbine blades in order to demonstrate their benefits [27–32]. The present study, however, is inclined to utilise flax fibre as the natural fibre in the composite. Flax is typically grown for its oil, and the stem is frequently used to extract natural fibres [33]. Flax fibres have a higher mechanical strength than other natural fibres, and their impact strength is determined under different loading conditions [34–37]. In addition, the tensile strength of flax-reinforced composites is further increased through the process of hybridisation. Flax farming requires less fertiliser and water than other crops and is well suited for large-scale commercial production [38,39]. As a result, they are also used to create various other sustainable products.

The present work further investigates the micro-size wind turbine blades made up of flax fibre composites, mainly suited for urban applications. The blades are developed using the CATIA software package and imported into the ANSYS mechanical workbench for numerical studies, including structural, modal, and harmonic analyses. These analyses demonstrate the feasibility and advantages of the natural composite over the existing synthetic-composite-based wind blades. Further sections begin with a literature review of similar composites, providing a comparison of similar studies, followed by the modelling of the wind blade, various numerical analyses carried out on the blade, limitations and scope of the study, and a conclusion.

2. Literature Survey

One of the most crucial parts of a wind turbine is the blades as they are subjected to extreme loads and environmental conditions. Synthetic composite materials have revolutionised the manufacture of wind blades due to their superior strength, durability, and environmental resistance. These composite materials, which are made of fibres embedded in a resin matrix, have shown to be an excellent choice for creating wind blades. As the wind energy industry continues to grow, manufacturers are encouraged to use synthetic composite materials to make wind blades that are both strong and lightweight.

The commonly used synthetic composite material in wind blade manufacture is E-glass/epoxy [40]. E-glass/epoxy composites are made up of E-glass fibres embedded in an epoxy matrix. E-glass is a type of glass that is designed to be used as a reinforcing material that is affordable, widely available, and resistant to fatigue. E-glass/epoxy composites have a high strength-to-weight ratio and can withstand a wide range of environmental conditions. However, they have limited stiffness and low resistance to high temperatures and create a huge impact on the environment at the time of waste disposal, since they are non-biodegradable in nature. E-glass/epoxy composites are ideal for use in small-to-medium-sized wind blades. S-glass/epoxy composites which are made of S-glass fibres can also be used in the wind blade manufacturing [41]. This type of S-glass fibre is much more durable and rigid than E-glass fibre and has an increased tensile strength and modulus. Although this composite can withstand a wide range of environmental conditions and is fatigue-resistant, they are more expensive than the earlier composites, are not biodegradable, and are more likely to be harmed by abrasion during very high wind loads.

Woven glass/epoxy is another synthetic composite material used in wind blade manufacturing [42]. These composites are made up of woven glass fibres embedded in an epoxy matrix. They are woven together in a specific pattern to achieve specific mechanical properties owing to their stiffness and strength. They can be manufactured with specific properties and have good fatigue resistance. However, they are expensive, susceptible to delamination, and non-biodegradable. These composites are ideal for use in large wind blades that require high stiffness and strength.

Carbon/epoxy composites have higher strength and stiffness when compared with Kevlar49/epoxy and glass/epoxy materials [43]. These composites are lightweight and have excellent fatigue resistance making them ideal for use in large wind blades that require high stiffness and strength. In addition, carbon/epoxy composites are costlier than glass/epoxy, non-biodegradable in nature, and require specialized equipment and expertise in manufacturing.

Considering the non-biodegradable nature of synthetic materials and their adverse effect on the environment leads the pathway to the research of biodegradable materials. Natural fibre composites such as pineapple/epoxy, sisal/epoxy, and bamboo/epoxy are partially biodegradable and are being researched for use in wind blade manufacturing. Pineapple/epoxy composites are made from pineapple fibres embedded in an epoxy matrix [44]. They are a by-product of pineapple farming, making them an environmentally friendly material. These composites have a high strength-to-weight ratio and are suitable for use in wind blade manufacturing. The composite matrix's void, cracks, and free space may lead to moisture absorption, weakening the bond between the fibre and the matrix.

Sisal/epoxy composite materials have high tensile strength, are light in weight, and have good fatigue resistance, making them suitable for use in wind blades [45]. They are also renewable and biodegradable, making them an environmentally friendly alternative to other synthetic composite materials.

Finally, flax/epoxy composite materials—discussed in this paper—are another renewable and biodegradable alternative to traditional synthetic composites. They are derived from the flax plant and have similar properties to those of sisal fibres and are suitable for use in wind blades considering their excellent fatigue resistance. They are cost-effective, less heavy, available in surplus, have good mould conformity, good consolidation, and higher fibre fraction, have a good strength-to-weight ratio, and most importantly are renewable and biodegradable [46,47]. The flax fibre employed in this study shares the same drawback as any other natural fibre with a hydrophilic character [48]. Figure 4 shows the weight comparison of micro-size HAWT blades manufactured from the mentioned composites, where it is apparently evident how lightweight flax-based composites are [41–43,45].

Synthetic fibres are typically derived from petroleum by-products. In contrast, natural fibres are mostly obtained from various renewable sources such as animals, plants, and minerals. During the natural fibre manufacturing process, it consumes fewer chemicals when compared to synthetic fibre production. Natural fibre composites usually comprise natural fibres and polymeric matrices. These composites can be used in numerous applications, such as building materials, door panels, Insulation boards, wind blades and so on. The waste disposal of these composite-based materials has less environmental impact when compared to their synthetic counterparts. This is mainly due to the partially biodegradable nature of these materials and their lower chemical signature in landfills. Additionally, it is worth mentioning that the burning of natural fibres does not produce any harmful gases. All these merits make natural fibre composites partially biodegradable in nature when compared with synthetic fibre composites.

From the review of the literature, it is inferred that there are various composite materials used in wind blade manufacturing in recent times. Mostly synthetic-fibre composite materials are utilized for this purpose because of their higher mechanical strength. However, the non-biodegradable nature of these synthetic composites makes them not suited for the environment. Many researchers continuously investigate the possibility of adopting suitable biodegradable material for wind blade manufacturing. Numerous studies investigate natural fibres like jute, hemp, bamboo, sisal, and coir for this purpose. The novelty in the present work is its aim to investigate flax-fibre-based wind blades for the application of micro-size wind turbines. To identify the performance and feasibility of the proposed wind blade, structural, modal, and harmonic analyses were carried out.

The static structural analysis of these wind blades is carried out using the finite element software tool ANSYS. The analysis confirms the stability and structural safety of the proposed wind blade under different wind load conditions. In addition to that, the resonance possibility of the proposed wind blade is analysed using modal and harmonic analysis. Finally, the obtained numerical results of the proposed wind blade are compared with other natural fibre-based wind blades, and the effectiveness of the flax/epoxy-based natural fibre wind blade is exhibited.

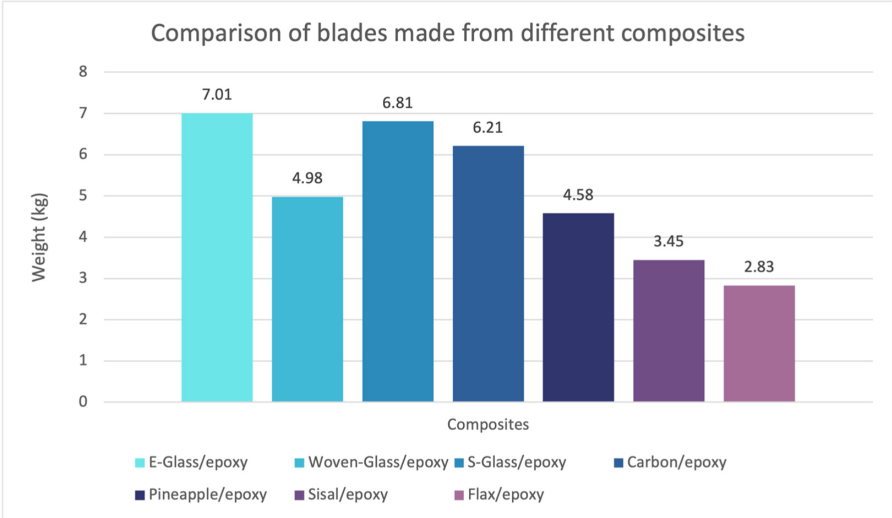

Figure 4. Weight comparison of blades made from different composites.

3. Aeroelastic Modelling of Wind Blade

Aeroelastic modelling studies the interaction between the aerodynamic forces acting on a wind turbine and its structural dynamics, playing a crucial role in comprehending how to characterise the aeroelasticity of wind turbine blades [49]. It involves simulating the behaviour of the wind turbine in response to wind loads and other external factors that affect its performance without physically building a structure. The modelling typically involves mathematical models that describe the motion and deformation of the wind turbine in response to the wind loads. The model considers the effects of wind turbulence, gusts, and other dynamic environmental factors that influence the performance of wind turbines. Aeroelastic effects on the blades can cause instability problems, including flutter and edgewise instability, which can have disastrous implications for the wind turbine blades. The model engineers optimize the design of wind turbines to improve their performance, durability, and reliability. It also helps to identify potential design flaws or operational issues such as the aeroelastic instability caused by increased span length and size of the blade. In order to characterise the cross-sectional attributes of wind blades, such as cross-sectional stiffness and mass per unit length, aeroelastic modelling often use a collection of 1D beam elements. This requires a specific cross-sectional analysis model due to the intrinsic characteristics of composite materials and the sophisticated design of the blade's structural architecture. When it comes to the complex field of aeroelastic modelling, engineers break it down into two crucial subcategories: aerodynamic modelling and structural modelling. To understand how a wind turbine will respond to wind forces, aerodynamic modelling is utilized to determine the specific forces acting on the blades. Structural modelling comes into play when predicting how the blades will respond to those forces. These subcategories are depicted in Figure 5 [49].

3.1. Aerodynamic Model of Wind Turbine Blades

The aerodynamic modelling of wind turbines utilizes four different types of models, namely, the computational fluid dynamic (CFD) model, the actuator type model, the vortex model, and the blade element momentum (BEM) model. In the present analysis, the wind blades are designed based on the blade element momentum theory [50,51]. The schematic of the blade element momentum model is illustrated in Figure 6 [49], where it is important to note that element theory ignores the interactions between the adjacent elements and discretizes the blade into many elements [52]. The local aerofoil characteristics, such as the drag and lift coefficients, of each element influence the aerodynamic loads applied to it. These loads are added together to calculate the overall loads acting on the blade. To calculate the induced velocity in the axial and tangential axes, respectively, the blade momentum theory incorporates axial and angular induction factors. Iteratively determining the performance characteristics of each blade element is possible by combining the blade momentum theory with the blade element theory. There are a number of limitations in the original BEM model, especially in its application for wind turbines. However, the majority of these limitations can be alleviated by adding empirical modifications based on the performance of the wind turbine.

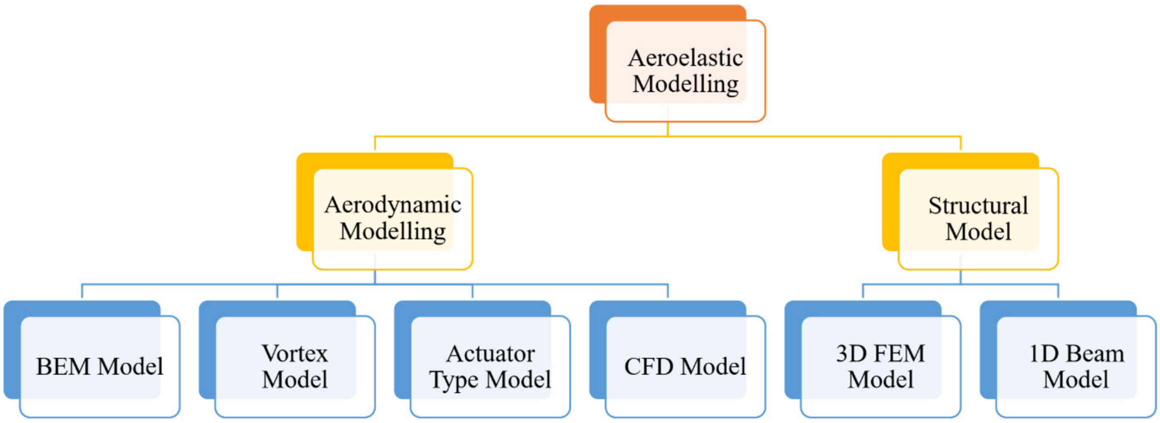

Figure 5. Main components of wind turbine blade aeroelastic modelling.

The capacity of the wind turbine and the location in which it is located have an impact on the shape and size of the wind blade. Micro-size wind turbines are better suited for urban applications and generate electricity from 500 W to 100 KW [53]. The quantity of power they produce is primarily influenced by wind speed, where they typically require a wind speed of 4 m/s. This would require that they be placed far from trees, large structures, and other potential wind-blocking obstructions in order to achieve a steady wind flow. In most metropolitan settings, rooftops offer a suitable location for their installation as they can provide the required steady wind flow. The typical span of the blades installed in these locations is between the length of 1.5 and 3.5 metres. Regardless of the length of the blades, the hub is designed and built with a strong aerofoil to increase robustness, where the tip and root of the aerofoil are made with different thicknesses. However, when it comes to the overall length of the blade, the amount of power produced by the rotor has the biggest impact on the decision. The formula expressed in Equation (1) is used to compute the usable output energy harvested from the turbine, while Equation (2) determines the effective radius of rotation (R_R). For low-speed smart city applications, a tip-speed ratio of 5 or 6 is chosen [54]. Equation (3) determines the tip-speed ratio (λ) and the Reynolds number is calculated from Equation (4), where micro-size urban HAWTs typically operate with a lower Reynolds number (R_e) [55]. The power and torque produced by the turbine are lowered if the selected aerofoil has a high R_e.

$$P_{rat} = C_P \eta \frac{1}{2} \rho A V_i^3 \tag{1}$$

$$R_R = \sqrt{\frac{2P_{rat}}{\rho \pi C_p v_{rat}^3}} \tag{2}$$

$$\lambda = \frac{r\omega}{V_s} \tag{3}$$

$$R_e = \frac{\lambda V_s C_P \frac{r}{R}}{U} \tag{4}$$

In the current numerical study, we analyse only one wind blade and assume that the other blades have similar geometry and boundary conditions. The NACA wind blade profile is chosen based on the design criteria and considerations. The chosen wind blade has a swept area of 3.14 m^2, a maximum chord of 0.2 m, and a span of 1 m. Figure 7 illustrates the precise dimensions of the micro-size wind blade used in the current work, while Figure 8 [56] illustrates how the lift and drag forces act on the wind blade due to the wind moving in different directions.

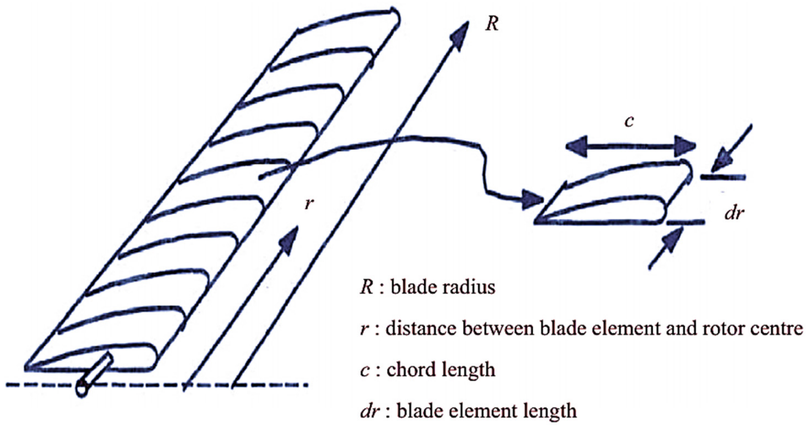

Figure 6. Blade element momentum model.

The lift forces (F_L) act normally to the apparent airflow while the drag force acts tangentially to the apparent airflow. These two forces are expressed mathematically in Equations (5) and (6). The values of these coefficients depend upon the shape of the aerofoil, angle of attack, airspeed, wing area, and air density. The values of these coefficients are determined empirically. The relationship between the drag and lift coefficient and the angle of attack is represented in Figure 9 [57]. The resultant forces (F_1 and F_2) are given by Equations (7) and (8).

$$F_D = C_D\left(\frac{\rho A U^2}{2}\right) \quad (5)$$

$$F_L = C_L\left(\frac{\rho A U^2}{2}\right) \quad (6)$$

$$F_1 = F_L \, sin\, \theta - F_D \, cos\, \theta \quad (7)$$

$$F_2 = F_L \, cos\, \theta - F_D \, sin\, \theta \quad (8)$$

3.2. Structural Model of Wind Turbine Blades

For structural modelling, the wind blade's three-dimensional model is developed using the design software package CATIA, shown in Figure 10a. The model is then imported into ANSYS Mechanical Workbench for numerical analysis. The ANSYS static structural solver is utilized for identifying the maximum deflection that occurs in the wind blade at different wind load conditions. The ANSYS modal analysis solver is used for determining the different mode shapes of the wind blade and modal frequency. The ANSYS harmonic response solver is utilized to calculate the maximum deflection and stress at the natural frequency of the particular wind blade [58]. The present work is adopting the aerofoil model NACA 4412 [59]. Prior to the numerical simulation, it is necessary to discretize the three-dimensional micro-scale wind blade's geometry into fine elements through meshing, as shown in Figure 10b. It is important to note that the accuracy of the result mainly depends upon the meshing process. The computational time increases with the increase in the number of elements [60–63]. The optimum size of the element during discretization is fixed based on the empirical process as explained in the forthcoming section. After meshing, the boundary conditions need to apply to the three-dimensional model of the wind blade as depicted in Figure 10c,d. As far as this study is concerned, the wind blade functions as a cantilever beam, where the force is imparted onto the wind turbine's bottom face. As a result, the proposed wind blade has meshed into 16,423 nodes and 38,542 elements in this analysis.

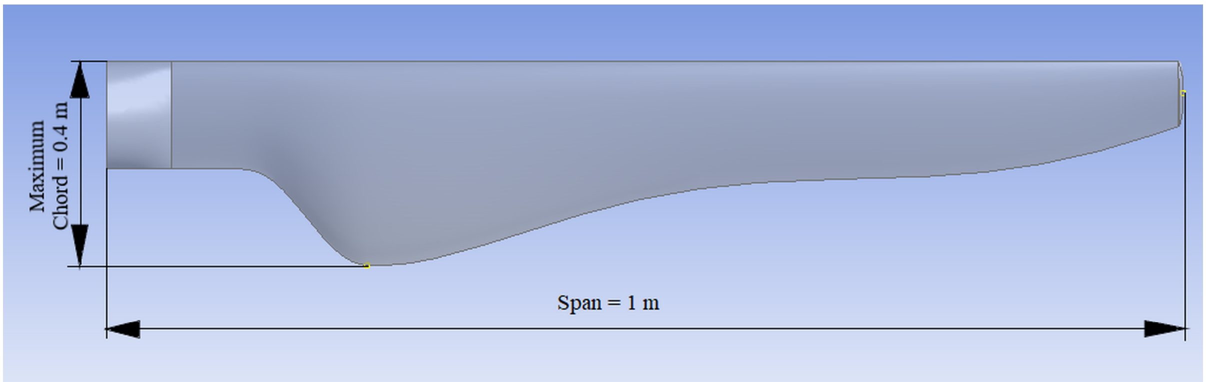

Figure 7. Micro-size wind blade model modelled in CATIA.

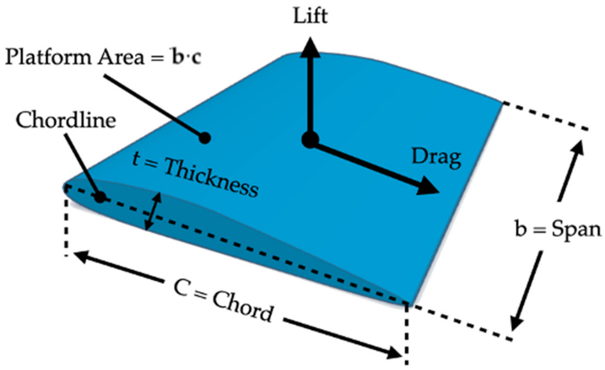

Figure 8. Drag and lift forces acting upon the HAWT.

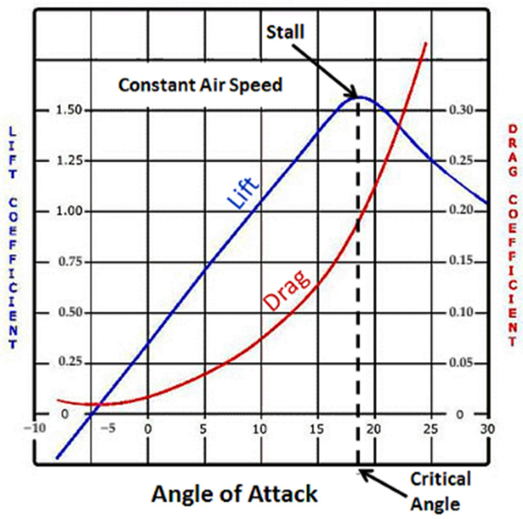

Figure 9. Relationship between C_D, C_L, and θ.

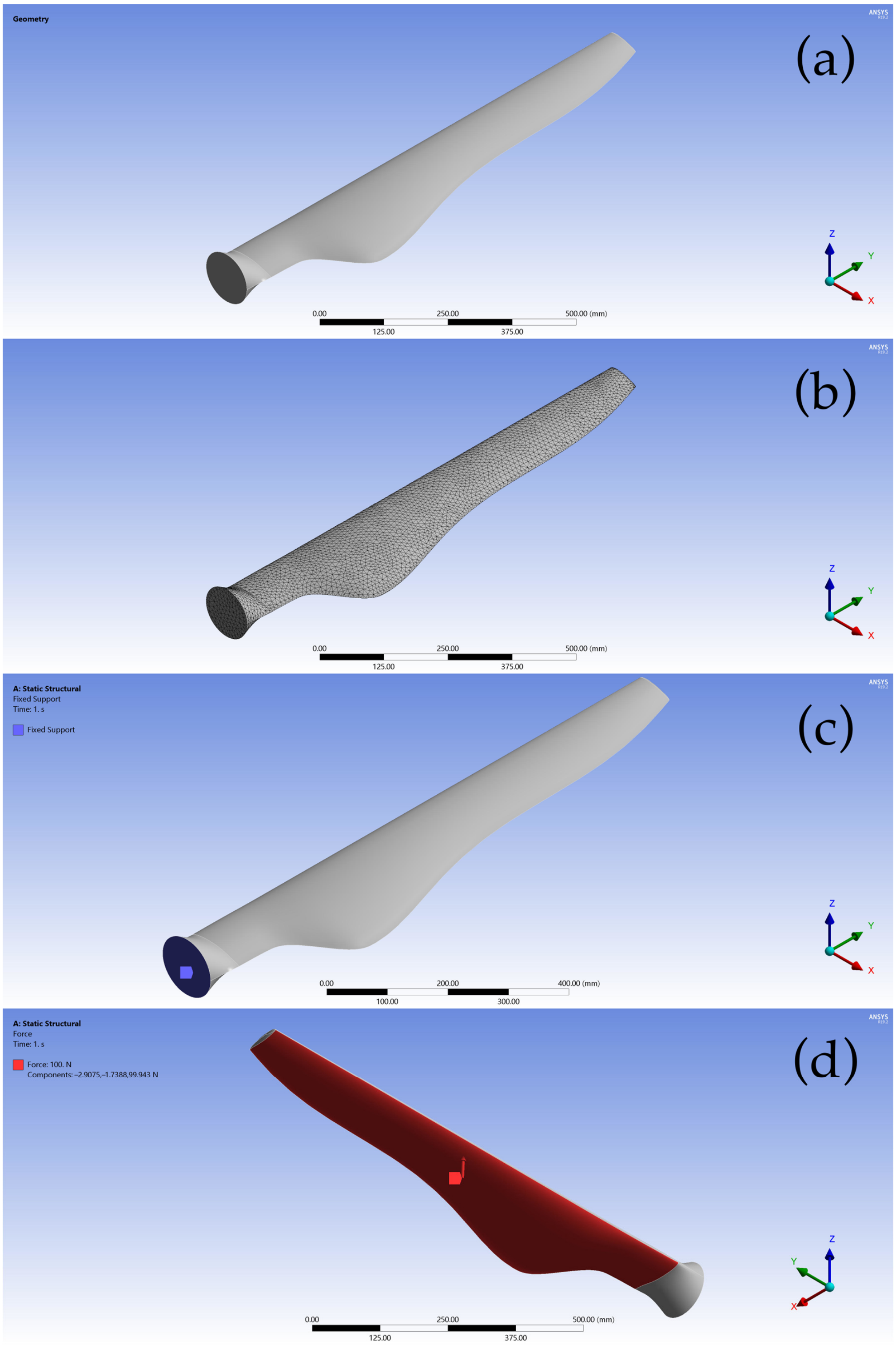

Figure 10. (**a**) Wind turbine blade structural design in ANSYS (**b**) Meshing of blade (**c**) Boundary condition applied on FEA model as a cantilever beam (**d**) Introducing wind load on the FEA model.

In the present work, natural fibres like flax, hemp, and coir are taken as a matrix, while the epoxy is taken as resin. The micro-scale wind blades are designed and developed using these natural-fibre-reinforced synthetic composites, and their performances are analysed. Numerous numerical analysis results including deformation, natural frequency, and peak amplitude, are compared, and the proposed wind turbine's prevalent characteristics are identified. In recent times, prepreg and vacuum-assisted resin transfer moulding are commonly used in the wet layup processes. Many wind blade manufacturers have begun to utilise vacuum-assisted resin transfer moulding for the layup process considering its economic feasibility. The blade is hollow in nature with a proper rolling operation carried out to remove the air bubbles and excess resin from the surface. In general, the outermost layer of the blade is the gel coat layer which provides a smooth surface to the blade and improves its aerodynamic properties. A layer consisting of soft materials that are relatively smooth and absorbent surface in nature is added to improve the adhesion between the underlying layer and the gel coat layer. The ninety-degree reinforcement is used to influence the thermal stability and to balance the layup. Normally, the thickness of the composite can be varied from 1 to 1.45 mm, while the total thickness of the blade wall is about 2 cm. At the trailing edge of the blade, the double-bias laminate splits into two layers to accommodate the core material. This laminate augments the strength of the blade's trailing edge.

4. Numerical Analysis

As explained earlier, structural, harmonic, and modal analyses are carried out to study the mechanical behaviour of the materials under different loading conditions. The detailed flow chart of process flow carried out in the numerical analysis is given in the flow chart for easy comprehension, illustrated in Figure 11. In the grid independence study, the influence of mesh size on the solution is critically analysed for effective numerical study in minimum computational time. For reducing the computational time and eliminating the mesh sensitivity on the numerical results, the coarse mesh is fine-tuned up to an optimal level. The wind turbine deflection has negligible difference while solving the numerical analysis having mesh grids of either 38,542 or 60,274 elements. Consequently, the mesh grid of size 38,542 elements is chosen for simulation to ensure minimal computational time and high numerical accuracy. Table 1 shows the variations of the blade-tip deflection with respect to the applied force.

Table 1. Grid impedance test results.

S. no	Total Number of Elements	Total Deformation (mm) at the Blade Tip for 100 N Wind Load
1	9053	11.65
2	13,653	10.38
3	26,789	8.14
4	38,542	4.62438
5	60,274	4.62127

4.1. Structural Analysis and Results

The structural analysis is done on a natural-fibre-reinforced composite blade to find the internal material resistance value against the applied load. Here, epoxy resin is chosen as the matrix material of the composite structure. The bidirectional orientation of fibre is used in the composite wind blade design since it has the capacity to withstand the two mutually perpendicular axis loads. In the bidirectional arrangement of fibres, the warp fibres absorb the applied loads while the weft fibres transfer the applied load in the transverse direction. Thus, the weft fibre prevents the stress from being concentrated on a small number of fibres. The analysis is carried out and compared between the conventional wooden blade and other blades made up of hemp-, coir-, and flax-fibre-reinforced epoxy blades, where the results show the static deformation for the applied loads. The load acting on the wind blade depends on the force of the wind acting on it. The maximum wind load value is then taken for the steady-state analysis.

From the aforementioned Equations (7) and (8), the resultant force value of the two mutually perpendicular axis forces acting on the aerofoil is calculated and considered in the numerical simulation. The basic equation for structural analysis is given in Equations (9) and (10), where Equation (9) is simplified to Equation (10) under steady-state conditions.

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{F(t)\} \tag{9}$$

$$[K]\{x\} = \{F\} \tag{10}$$

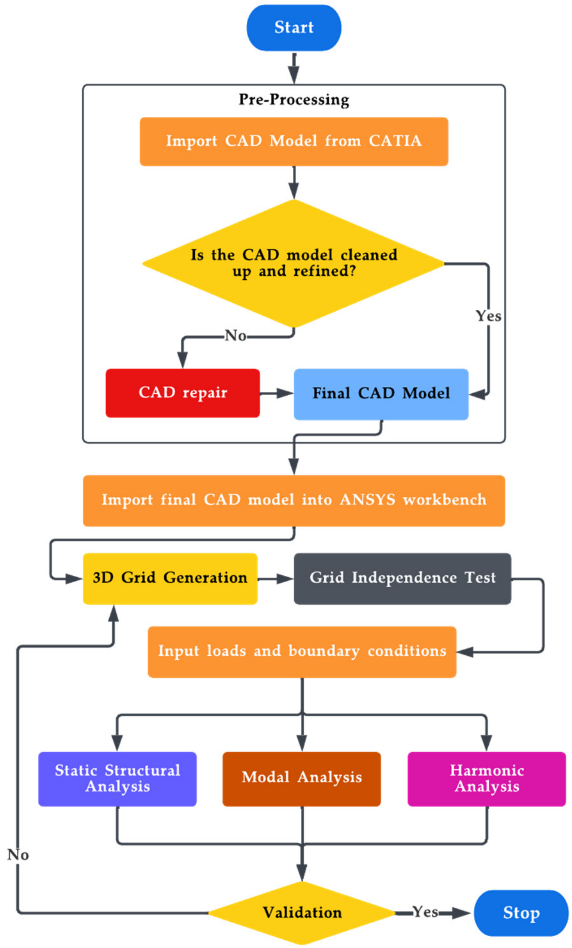

Figure 11. Introducing wind load on the FEA model.

In the present study, the micro-size wind turbines used in urban areas are taken into consideration. The wind load is assumed as varying up to 100 N. The results of the analysis identify the deflection profile of the wind blade for the applied load, where the deflection on every nodal point is easily calculated from the contour profile. In the case of a cantilever beam, the largest deflection is attained at the blade tip. The wooden blade has a deflection value of 142.61 mm at the free end, illustrated in Figure 12a. The wooden wind blade deflects more than other types of blade, due to the low elastic modulus of the wood. The blade made of hemp-fibre composite shows a deflection of 5.376 mm, shown in Figure 12b. The coir-fibre-reinforced composite blade shows a deflection of 22.756 mm, as shown in Figure 12c, while the flax-fibre-reinforced blade shows a deflection of only 4.624 mm, which is illustrated in Figure 12d. The deflections of the various blades under progressive loads are compared in Figure 13. In general, for the design of the wind blade, materials with lower density and higher modulus of elasticity are preferred. The values of such physical properties of the materials adopted in the study are compared in Table 2 [44,64,65].

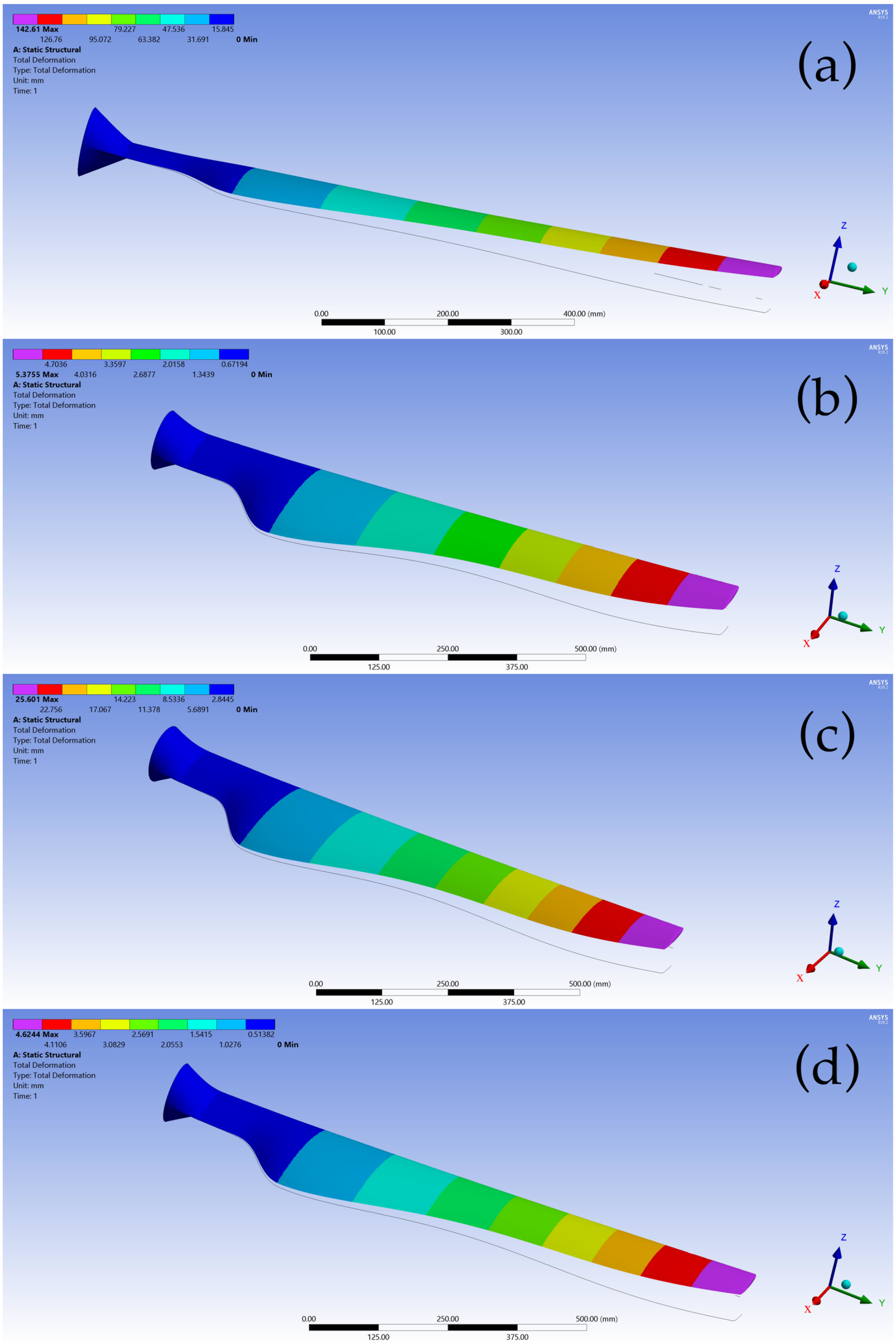

Figure 12. Total deformation of (**a**) wooden blade (**b**) hemp-fibre-reinforced blade (**c**) coir-fibre-reinforced blade (**d**) flax-fibre-reinforced blade.

In their initial days, wind blades were made of wood and were not structurally feasible for high-wind-load applications. Thereafter the wind blades are manufactured using structural steel. It offers good mechanical strength to the blades but it is heavy. To reduce the weight and keep good mechanical characteristics, synthetic fibre materials have been introduced in wind blade manufacturing. But these synthetic materials are costly and non-biodegradable in nature. There is continuous research to identify suitable and biodegradable materials for wind blade manufacturing. In this context, numerous researchers propose jute, hemp, bamboo, sisal, and coir. The present work investigates flax-fibre-based wind blades for micro-size wind turbines. The structural, modal, and harmonic analyses were carried out to identify the performance and feasibility of the proposed micro-size wind blade.

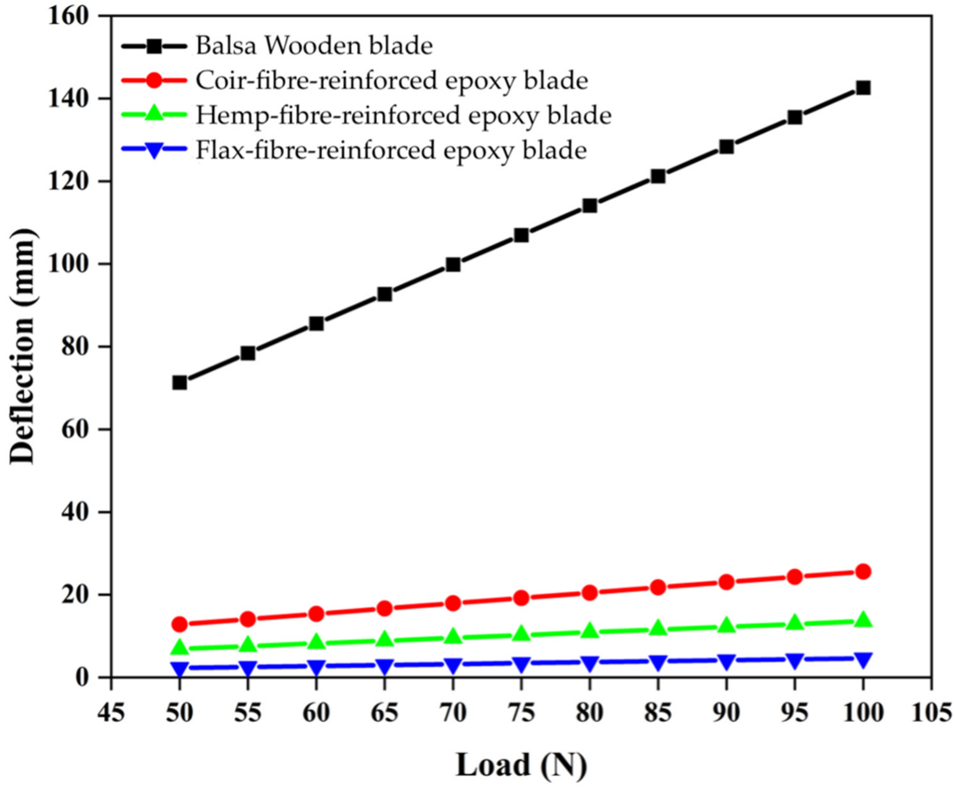

Figure 13. Comparison of wind blade deflection.

Table 2. Mechanical strength of different materials used for wind blade manufacturing.

Properties of Different Materials	Balsa Wood	Hemp Fibre Composite	Coir Fibre Composite	Flax Fibre Composite
Density, kg/m^3	160	1346.8	1150	1365
Y's * Modulus (E_x) GPa	0.89	23.968	5	27.393
Y's Modulus (E_y) GPa	0.89	23.968	5	27.393
Y's Modulus (E_z) GPa	0.89	3.3	3.3	3.3
Poisson's ratio, ν_{xy}	0.38	0.221	0.3	0.396
Poisson's ratio, ν_{yz}	0.38	0.221	0.3	0.396
Poisson's ratio, ν_{zx}	0.38	0.32	0.32	0.32

* Lower density, higher Young's Modulus (Y's) and lower Poisson's ratio are more suitable for wind blades.

4.2. Modal Analysis and Results

In modal analysis, the wind blade dynamic characteristics are analysed for vibrational excitation, along with the calculation of the mode shape and natural frequency values of the wind blades [66]. The resonance condition of the component is based on its geometrical shape and the value of its density. Thus, generally speaking, the resonance conditions of the composite wind blade are found using modal analysis. The resonance value of the component is higher for the consequent mode shapes and is calculated using ANSYS. The analysis helps the designer understand how the wind blade behaves under different dynamic loading conditions allowing modification of the design for a higher resonance. Another factor to be aware of is the natural frequency, which refers to the frequency at which the blades vibrate when in free vibration conditions [67]. This frequency range is typically between 0.5 Hz and 30 Hz and is mainly influenced by the number of blades (3–5) and revolutions (1.5–2 Hz) [68]. Higher values of natural frequency are preferred within the specified range, as they can benefit the turbine by increasing its stiffness and reducing the risk of fatigue failure [67]. For calculating the free vibration value, the general equation to find the resonance value at different mode shapes is determined using Equation (11), while for the simple harmonic function, the basic solution equation is calculated using Equation (12). Equation (13) is derived by substituting Equation (12) in Equation (11). Thereafter, Equation (13) is simplified as Equation (14) by substituting λ as ${\omega_n}^2$. The obtained first modal frequency values of wood-, hemp-, coir-, and flax-fibre-reinforced blades are 10.074 Hz, 17.874 Hz, 8.657 Hz, and 19.155 Hz, respectively. The obtained values for different modes are compared in Figure 14 while their individual values are shown in Figure 15. From the result of the analysis, it is evident that flax-fibre-reinforced blades have shown the highest natural frequency at 19.155 Hz.

$$[M]\{\dot{u}\} + [K]\{u\} = \{0\} \quad (11)$$

$$\{u(x, y, z, t)\} = \{\varnothing(x, y, z)\}e^{t\omega_n} \quad (12)$$

$$\left[K - {\omega_n}^2 M\right] = \{0\} \quad (13)$$

$$|K - \lambda M| = \{0\} \quad (14)$$

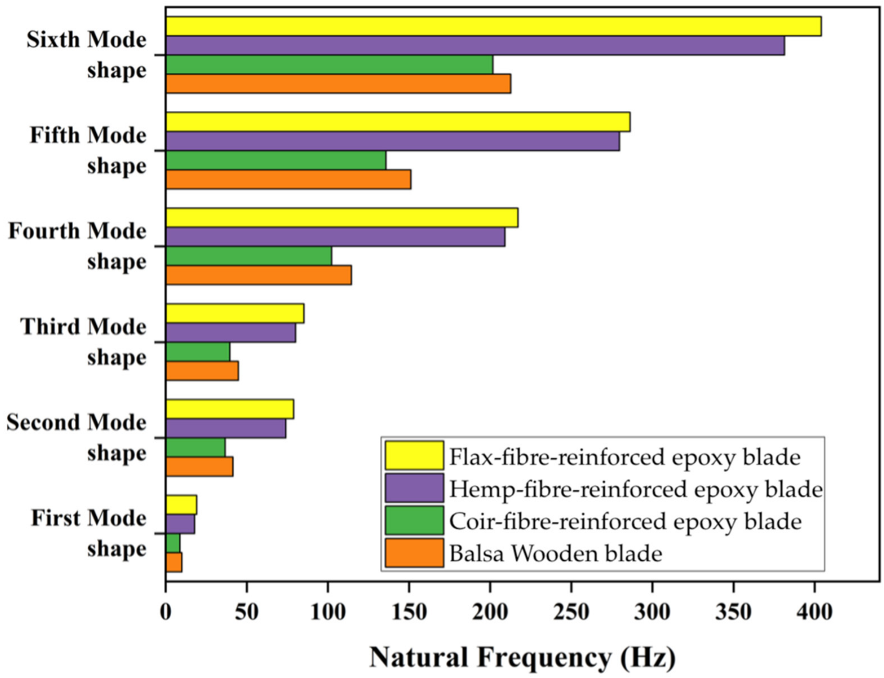

Figure 14. Natural frequency of the wind blade made of different materials.

4.3. Harmonic Analysis and Results

The amplitude of the wind blade at the resonance conditions along with the induced stress due to the wind blade deflection on vibrational load is calculated from the harmonic analysis. This variation of amplitude and stress value under different vibrational loads guides the designer to design the wind blade to withstand heavy loads on cyclic loading conditions [69]. The variation in the stress of wind blades with different materials at various frequencies is represented in Figure 16. Figure 17 demonstrates that the flax-fibre-reinforced wind blade has a stronger rigidity than the other blades with different materials and thereby reaches resonance at a higher frequency. In this computational analysis, the viability and adaptability of the wind turbine for applications in urban areas are investigated along with the natural composite HAWT. Furthermore, the proposed wind turbine can be implemented in a real-time hardware setup under an experimental configuration in the future.

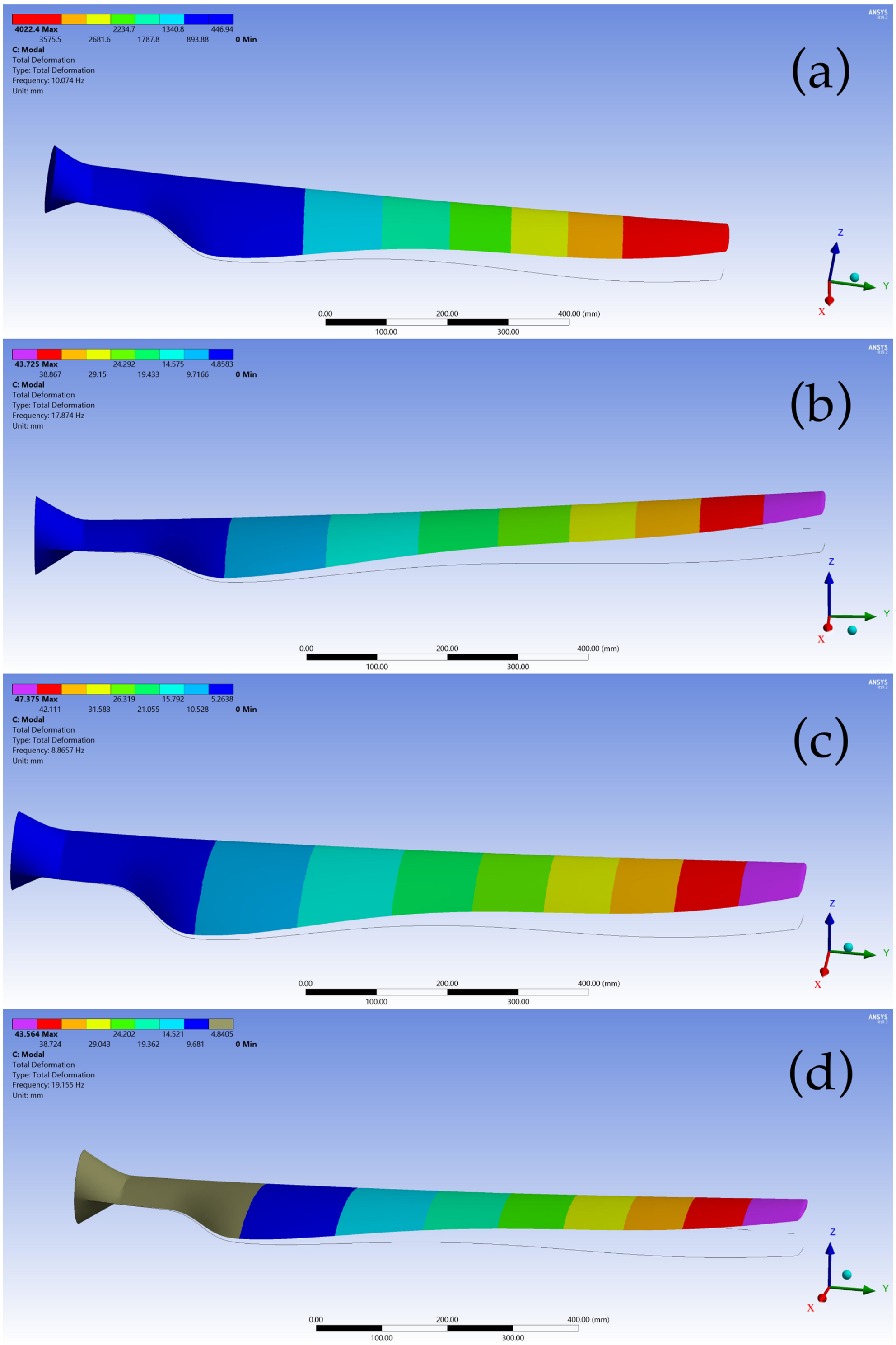

Figure 15. Natural frequency of blade at first mode shape (**a**) wooden blade (**b**) hemp-fibre-reinforced blade (**c**) coir-fibre-reinforced blade (**d**) flax-fibre-reinforced blade.

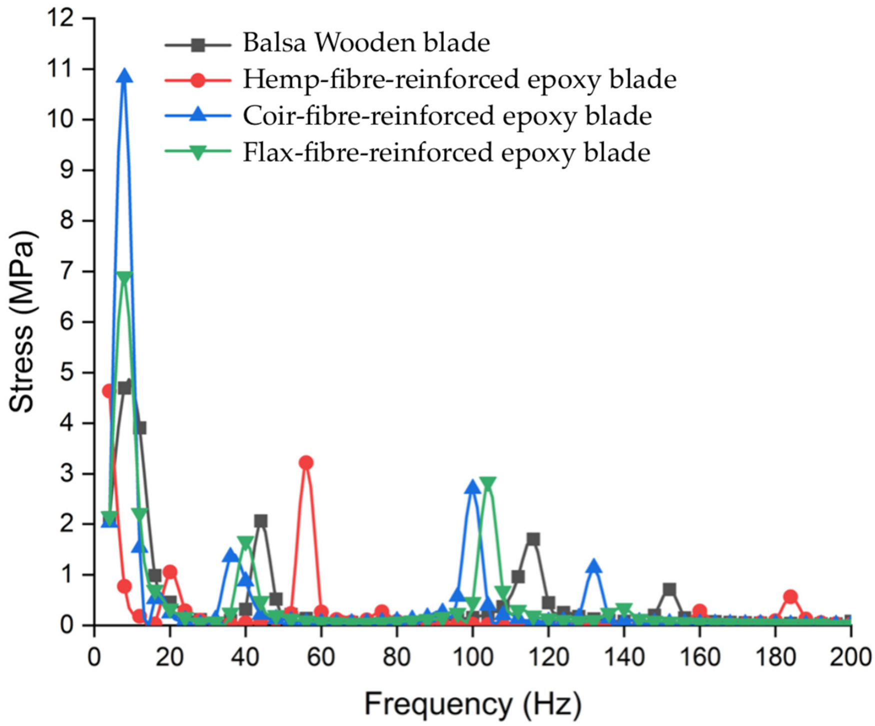

Figure 16. Variation of the stress in wind blades with different materials with respect to different frequencies.

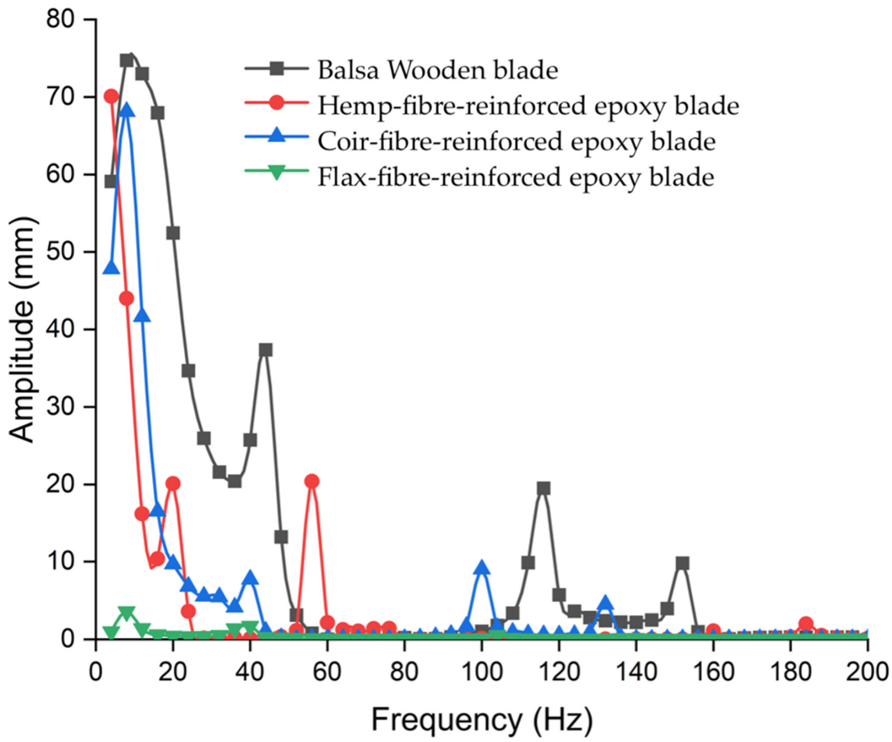

Figure 17. Variation of the displacement amplitude in wind blades with respect to different exciting frequencies.

5. Limitations and Future Scope of the Present Study

The study explores the use of flax-fibre-based micro-sized HAWTs for urban applications. The manuscript includes a detailed analysis of the turbine's structural, modal, and harmonic properties, as well as an in-depth aerodynamic study of the proposed blade. To further improve the accuracy of the results, the study can be extended to include computational fluid dynamics analysis. The study shows that the proposed natural-fibre wind turbine performs better under a maximum wind load of 100 N. However, it is essential to note that wind loads can vary depending on geographical location, and the study does not account for the effects of water absorption or moisture in the atmosphere. Natural fibres lack interfacial adhesion if not appropriately treated, and exceeding the processing temperature limit of 200 °C weakens the composite [70]. Low dimensional stability leads to swelling and shrinkage, but proper fibre surface treatment can address these limitations. Properties can be customized for specific application areas, and future studies can consider these factors for improved results. Currently, the study is limited to numerical analysis, but future work can focus on the hardware realization of the proposed wind turbine.

6. Conclusions

The present study investigated the feasibility of using natural fibre like flax-fibre-reinforced composite in micro-sized HAWTs for urban areas and smart cities. The use of natural fibres is advantageous due to their moderate stiffness, biodegradability, higher modulus of elasticity, and eco-friendliness. In the current study, the wind blades are designed using CATIA and subjected to modal, harmonic, and structural analyses under different loading conditions in ANSYS. Balsa wood and three different natural-fibre composites, which include flax fibre, are taken as wind blade material, and investigations are carried out. The numerical results revealed that the wooden blade experiences significant deformation due to its lower modulus of elasticity. In contrast, blades made of natural composites such as hemp, coir, and flax show modest deflection. Results indicate that the flax-fibre-reinforced synthetic-composite-based blade has the least deformation among the natural-fibre composite blades, around 5 mm for maximum wind load conditions. Similarly, modal and harmonic analysis demonstrate that the flax-fibre-reinforced blade has a higher modal frequency, greater stiffness, and less vibration than the other blades. Results revealed that the flax-fibre-reinforced blade has a higher natural frequency of around 400 Hz in a sixth-mode shape and experiences the least deflection and minimum stress in natural frequency. Based on these findings, we conclude that the proposed flax-fibre-reinforced natural composite blade is lightweight, eco-friendly, less vibrational, more stable, and suitable for placement on rooftops in urban environments. Furthermore, the biodegradable nature of the proposed natural wind turbine makes it more sustainable.

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Nomenclature

R_R	Radius of rotation
λ	Tip-speed ratio
R_e	Reynold's number
r	Radius of rotation for generator
ω	Angular velocity
V_s	Rated wind speed
P_{rat}	Rated power
C_p	Power coefficient
V_i	Incident wind velocity
ρ	Air density

η	Efficiency
r	Hub radius
U	Kinematic viscosity
A	Swept area
F_L	Lift force
F_D	Drag force
C_L	Lift coefficient
C_D	Drag coefficient
θ	Angle of attack
$[K]$	Stiffness matrix
$\{x\}$	Displacement
$\{F\}$	Force vector
$\{\varnothing(x, y, z)\}$	Amplitude
ω_n	Angular frequency

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