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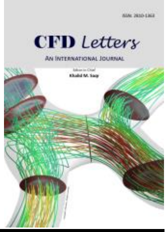

Simulation Study of the Effect of Wind Speed and Material Type on the Mechanical Properties of Vertical Axis Wind Turbine Blades

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ABSTRACT

Wind energy is a clean and fast-growing renewable energy source that can be harnessed using wind turbines. In a Vertical Axis Wind Turbine (VAWT), turbine blades are a crucial factor, and their fiasco leads to wind turbine failure. However, references to VAWT blade structural analysis are very limited. Therefore, the study was carried out to determine the material with the lowest degree of deformation without structural failure. The finding could be used as a recommendation in the material selection of Savonius type vertical axis wind turbine blades. The study used materials such as aluminum, stainless steel, and fiberglass. The analysis was carried out by simulating using ANSYS software. Computational Fluid Dynamics (CFD) was used for determining the loading by providing speed variations at 3 m/s, 4 m/s, 5 m/s, and 6 m/s. The Finite Element Analysis (FEA) method was applied to analyze the structure, which shows the results of total deformation, equivalent stress, and safety factor. The total deformation results from the aluminum blades showed values of 109.55 mm, 190.73 mm, 299.25 mm, and 425.39 mm. The safety factor values of 4.4049, 2.5166, 1.5647, and 1.1348 revealed that it was also technically safe. Aluminum material can be recommended to be used in the manufacture of Savonius type vertical axis wind turbine blades because of its low price, lightweight, corrosion resistance, and sufficient durability, as revealed from the results of total deformation and safety factor values.

1. Introduction

Currently, the use of non-renewable energy sources, such as fossil fuels, is very high. This problem also has an impact on environmental issues. Under such conditions, dependence on non-renewable energy must be conditioned and directed towards many renewable energy sources like solar energy, wind energy, water energy, tidal energy, geothermal energy, and biomass energy [1]. Renewable energy issues encourage research on the further development of renewable energy.

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Wind energy is clean and fast enough to meet the viable energy needs of the global community [2–5]. Wind energy sources in Indonesia are abundant, with an estimated capacity to produce 61 GW of electricity, however, this potential has not been fully utilized. The wind turbines that have been installed so far only produce 154 MW of electricity [6]. Although the average incoming wind speed in Indonesia is relatively low, about 3 to 7 m/s, there is potential to increase the capacity of wind-sourced electrical energy in Indonesia [7].

In 1922, Sigurd J. Savonius created the first Savonius wind turbine. This type of drag-type turbine matches the low speeds, such as in Indonesia. Wind energy is advantageous in that it has the ability to receive wind from all directions, is facile and cheap to produce, and can rotate with a relatively low angular speed [8, 9]. Savonius's wind turbine is driven by drag. The aerodynamic efficiency of this wind turbine is lower than that of other wind turbines, such as the Darrieus rotor. However, the Savonius rotor is reliable and of simpler form, with strong starting torque and no problems with wind direction [10, 11].

The development of wind turbines is carried out by developing various components, including turbine blades. Wind turbine blades are the most crucial part of the turbine. In industry, the selection of turbine blade materials is very important [12]. Wind turbine blades must meet several requirements to qualify as aerodynamic structures, such as durability, low price, low weight, low density, and resistance to corrosion and fatigue [13–15]. In a Vertical Axis Wind Turbine (VAWT), turbine blades are an important component, and their failure leads to wind turbine collapse. Unlike horizontal-axis wind turbines, VAWTs do not have cantilever blades as a feature, and consequently, VAWTs experience fewer fatigue problems. However, not many studies have reported on the structural analysis of VAWT [16]. Therefore, it is necessary to develop the structural analysis of VAWT blades to obtain blades with good performance.

A study on the structural design and stress analysis of helical vertical axis wind turbine blades using aluminum material explained that this material is recommended to be applied in the manufacture of VAWT turbine blades. This is due to the small displacement value and von Mises values, which are at the end of the blade, so that it is far from structural failure. This analysis used ANSYS software for loading using Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) for stress analysis [17]. Saravanan & Muthurajan [18] stated that aluminum is recommended for the manufacture of wind blades at a lightweight, low cost without compromising the performance and stability of the turbine blades after conducting a modal analysis on a two VAWT aluminum blade to identify the response of the structure to dynamic loading.

Developing wind turbine blades using stainless steel is a smart move. Stainless steel is known as a material with high resistance to corrosion [19]. According to Rahman M *et al.,* [20], who carried out a finite element analysis to optimize the structural design of various models of vertical axis wind turbines using a variety of materials, the blades made of stainless steel have the lowest deformation value. Saravanan & Muthurajan [21], in their research on the capital analysis of two VAWT Savonius blades made of stainless steel, explained that stainless steel is suitable for making turbine blades because there is no structural failure.

Kumar *et al.,* [22] performed vibration fatigue analysis on NACA 63215 small horizontal axis wind turbine blades to produce deformation output, principal stress, safety factor, and life estimation for each material variation. The simulation results showed that Glass Fiber Reinforced Plastic (GFRP) material is safer for small horizontal axis wind turbine blades. García *et al.,* [23] performed finite element analysis on wind turbine blades with a variety of fiberglass and basalt fiber materials by applying the ANSYS CFD method for loading the wind speed. However, the study used the model of turbine blades Horizontal Axis Wind Turbine (HAWT) at relatively high speed.

According to research conducted by Appadurai and Raj [24], finite element analysis of HAWT turbine blades made from composites revealed the difference in yield of each material. In this study, a comparison chart of equivalent von Mises stresses with force variations was made. The higher force given resulted in a higher von Mises stress value experienced by the turbine blades. However, the carried-out analysis did not provide a safety factor value because the possibility of structural failure in the material was not known. This research was done with the aid of ANSYS software for finite element modeling and analysis with specified stiffness and strength constraints on specimens [25, 26].

Based on the above description, only a few studies related to the structural analysis of Savonius type wind turbine blades are available. Previous analysis has been carried out using a two-blade model without using the CFD method for loading using direct wind speed. The failure rate of the structure using the safety factor was not shown by the given results. Therefore, further studies to examine the structural analysis of the Savonius type wind turbine blades using a three-blade model and a combined method of CFD and FEA are needed. The use of CFD and FEA methods is intended to adapt to conditions on the ground using wind speed. This study discussed the structural strength of the material used in the manufacture of wind turbine blades, which includes total deformation, equivalent stress, and safety factor. The purpose of this study was to obtain a material that has a low deformation rate without any structural failure and can be recommended for the manufacture of Savonius type vertical axis wind turbine blades. To get the best choice of material, the results of the research on the three materials were compared by calculating several loading conditions, analyzing them, and using computational techniques using the ANSYS device.

2. Methodology

2.1 Wind Turbine Blade Models

Wind turbine modeling is a method used to design and provide specifications for wind turbine blades. This study focused on the application of vertical-axis wind turbines due to the commonly used for small to medium-scale power plants. This type of turbine is also widely used in urban or rural areas because of its flexibility.

The analysis in this study used the Savonius type vertical axis conventional wind turbine model. SOLIDWORKS software is used to model turbine blades [27]. The prepared model was entered in the Design Modeler on ANSYS. The three-blade type with variations in speed and material used in the selected vertical axis wind turbine. Figure 1 shows a wind turbine blade with a 1030 mm length, 3mm thickness, and a 120° bend angle.

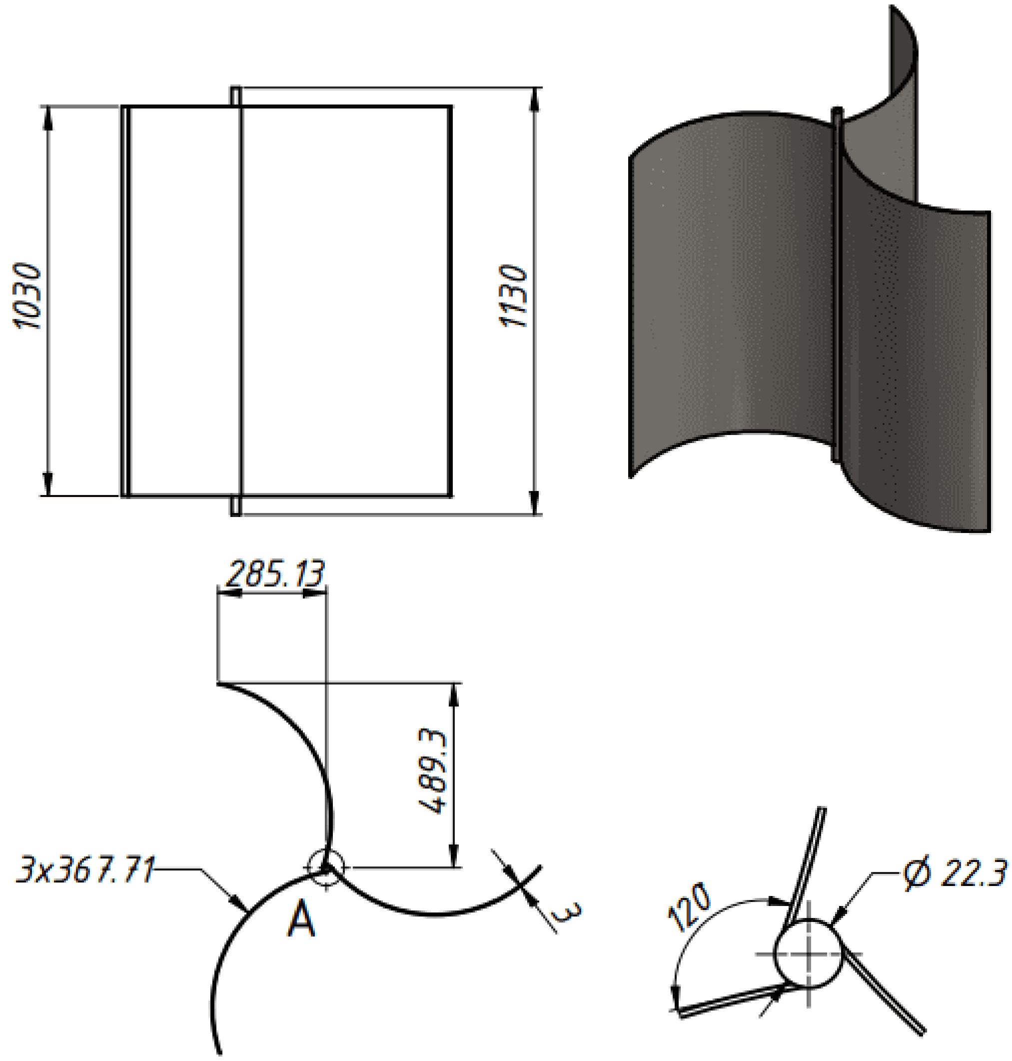


Fig. 1. Blade Model of the Savonius Type Vertical Axis Wind Turbine (Unit in mm)

2.2 CFD and FEA Modeling

The analysis process in this study used the CFD method combined with the FEA method [28]. The wind turbine blade CFD process method used ANSYS Fluent [29–31], which is the most widely used modeling for CFD. The model was then applied to the CFD modeling of the Savonius vertical axis wind turbine blades. In this CFD method, the computation was carried out by including mesh, boundary conditions, computational domain, and turbulent modeling. The overall simulation process is depicted in Figure 2.

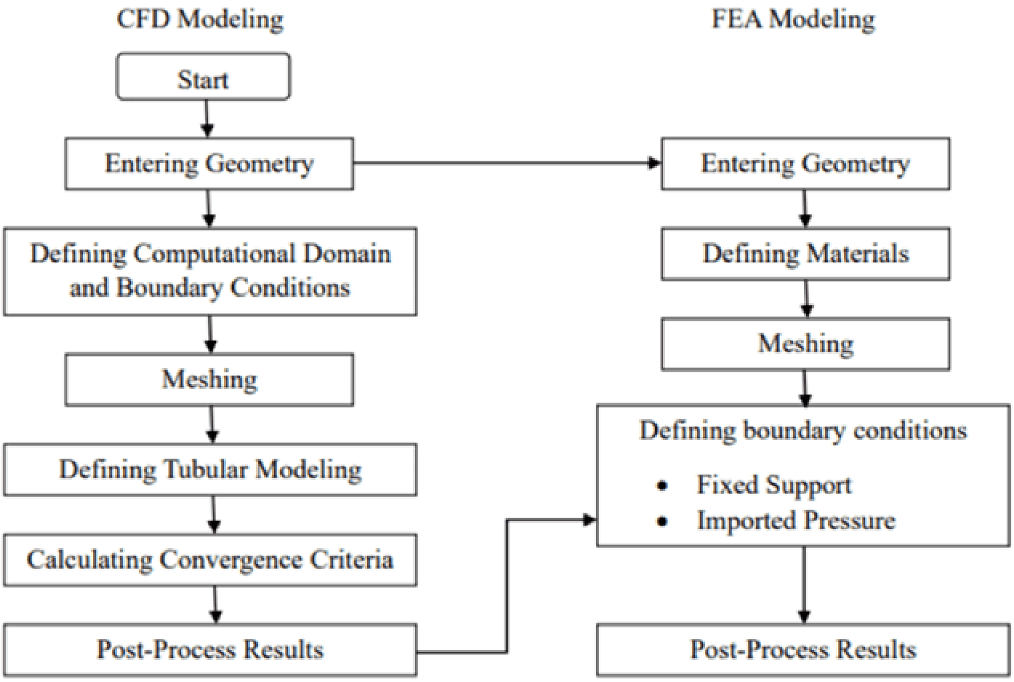


Fig. 2. CFD and FEA Modelling Procedure

2.2.1 Computational domain and CFD boundary conditions

The Savonius type vertical axis wind turbine blades have a symmetrical shape with respect to the center of rotation. The three fixed blades were modeled in this analysis for accurate results. In CFD modeling, turbine blades were inserted into the tunnel or computational domain to provide space for the fluid used. Adjusting the shape of the Savonius type wind turbine blades, the computational domain used a beam shape, and wind speed was used as the fluid.

The computing domain was divided into three parts, i.e., inlet, outlet, and wall sides. At the inlet, wind speeds varied between 3 m/s, 4 m/s, 5 m/s, and 6 m/s. The wind speed was entered into the inlet side, which is 1000 mm from the turbine, and set to free-stream wind speed. Atmospheric pressure was set on the outlet side to a distance of 3000 mm from the turbine. The conditions were chosen to eliminate any effect of the domain boundaries on the flow around the turbine. Meanwhile, the free-stream wind speed was used to adjust the use of the turbine in a resistance-free flow field [32, 33]. In this computational domain, the received temperature was neglected. The turbine blades were considered stationary non-slip walls or no-slip boundary conditions because no movement occurred between the blades and the given fluid. This was used to avoid rotating meshes and the possibility of unstable turbine blade problems, as well as significantly reduce computation time. The computational domain for the model is seen in Figure 3.

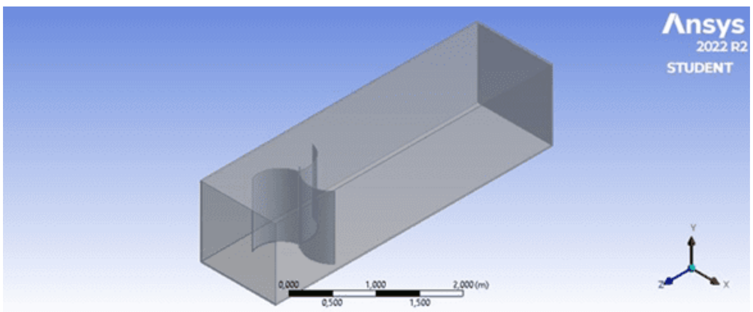


Fig. 3. Computational Domain for CFD Modeling

2.2.2 CFD meshing

After the model was combined with the computational domain, meshing was performed on the computational domain. Meshing is a technique for discretizing a computational domain into cells or parts. The convergence and accuracy of the CFD results are affected by the given meshing. In this study, triangular mesh elements were used [34]. A better meshing quality resulted in a more appropriate flow solution. Therefore, a longer computation time was needed. In this analysis, the given CFD meshing size was 25 mm according to a previous study [17, 33]. Meshing in the computational domain of the Savonius type vertical axis wind turbine blades is given in Figure 4.

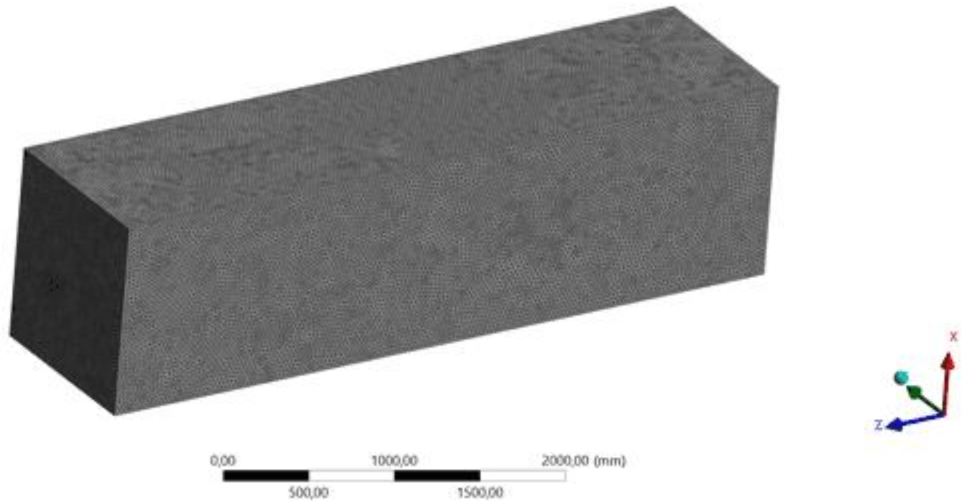


Fig. 4. Computational Meshing Domain of Savonius Type Vertical Axis Wind Turbine Blades

2.2.3 Turbulence modeling

The application of flow in CFD simulations is an unavoidable factor. There are several turbulence models that can be used, such as Direct Numerical Simulation (DNS), which is used in the direct approach to solving fluid mechanics equations; Large Eddy Simulation (LES), which can be used to directly solve large eddy flows; or Reynold Averaged Navier-Stokes (RANS), which calculates the average of the flow fluctuation values. In this research, the Reynolds averaged Navier-Stokes model was used for turbulence modeling.

The RANS turbulence model used for this research was k-ε. The k-ε turbulence model is the most widely used model in computational fluid dynamics (CFD) to simulate average flow characteristics for turbulent flow conditions. This is a two-equation model that provides an overview of turbulence through two transport equations. The first transported variable is the turbulent kinetic energy (k), and the second transported variable is the turbulent kinetic energy dissipation rate (ε). This model has the advantage of solving streams with high Reynolds numbers, such as free streams.

2.2.4 Post-process results

Because the wind movement changed continuously, nonlinear fluid flow was used. Therefore, the CFD solution must be calculated iteratively. In this study, the number of iterations carried out was 100, which was sufficient to ensure iterations. In addition, a standard initialization method was used to solve this problem, and an initial value of the inlet limit was calculated. Simulation results were plotted using post-processing on ANSYS Fluent. CFD simulation results, such as aerodynamic pressure and torque acting on the blade, could be plotted. Because the geometry and solutions in ANSYS Fluent are related to static structural analysis for Finite Element Analysis (FEA), the simulation results were not displayed for analysis results.

2.3 FEA Modeling

The FEA model of the Savonius type vertical axis wind turbine blades was made using the ANSYS static structural module, which is the most widely used FEA modeling software. As previously explained, this turbine blade finite element analysis used the import of boundary conditions in the form of wind speed, connected via ANSYS Fluent with ANSYS static structural on the workbench menu. This section presents the geometry, material properties, mesh, and boundary conditions used in the FEA modeling.

2.3.1 Selection of material properties

Three materials were used in this study: aluminum, stainless steel, and fiberglass. The selection of this material was based on references to previous journal articles that explained the advantages of the materials as well as the recommendations for their application in small-scale wind turbines. This selection was considered in developing a vertical axis wind turbine with a low speed at Semarang, Indonesia. There were four main selection criteria for the development of this wind turbine blade: price, lightweight, corrosion resistance, and durability. Table 1 shows the properties of the materials used in this research.

Table 1
Material Properties

Properties	Aluminum [17]	Stainless Steel [35]	Fiberglass [27]
Young's Modulus, E (MPa)	71,000	1.93×10^5	73,000
Poission Ratio, v	0.33000	0.31000	0.22000
Density, ρ (kg/mm^3)	2.77×10^{-6}	7.75×10^{-6}	2.6×10^{-6}
Tensile Yield Strength (MPa)	280	207	521
Tensile Ultimate Strength (MPa)	310	586	3,400

The aluminum alloys contain about 85% aluminum as the main metal. Typical alloying elements are manganese, silicon, silicon dioxide, copper, tin, zinc, and magnesium. There are two different types of aluminum alloys: casting alloys and wrought alloys, which are classified as heat-treatable and non-heat-treatable, respectively. The alloy has outstanding mechanical characteristics and high chromium content. Aluminum alloys are used by manufacturing industries to design structural elements and engineering components where high corrosion resistance and a ratio of lightness to strength are required. The surface of the aluminum alloy metal is covered by a thin layer of oxide, which protects the metal from air attack.

As an alloy with a maximum of 1.2% carbon by mass and a mass content of 10.5% chromium, stainless steel is sometimes referred to as inox steel. The 316 used in this study is widely known for its excellent corrosion resistance and is used in the development of household goods, building materials, and industrial machinery. When compared to aluminum alloys, the 316 alloys are heavier. Metal oxides or hydroxides, which contain certain corrosion by-products, are formed when stainless steel reacts with air. Although the use of stainless steel in the development of wind turbine blades is an extraordinary concept, it will increase the blade failure rate as stainless steel reacts with air.

Fiberglass is an effective material used in small-scale wind turbines because of its lightweight and good resistance [36]. Fiberglass consists of a variety of fine glass fibers that also have high mechanical, chemical, and thermal properties. Most the glass fiber reinforced is made of electric glass, which has good electrical and heat resistance. Glass fiber has characteristics of high strength, suitable stiffness, and proper density. Unfortunately, glass fiber has low fire resistance.

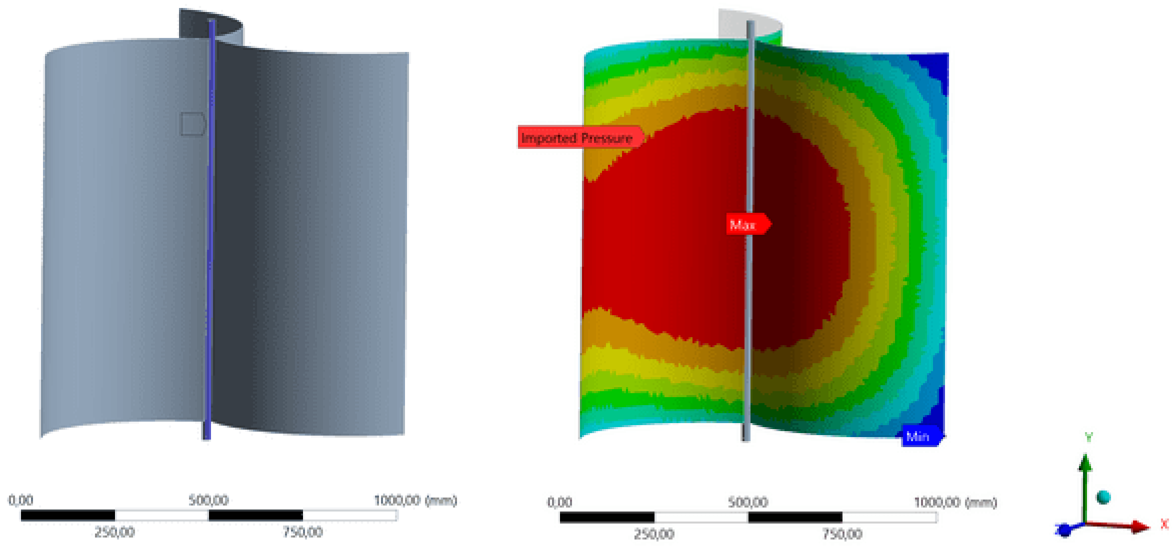
2.3.2 Meshing FEA

The meshing process was also performed using finite element analysis (FEA) to discretize components. However, in FEA, the meshing components were focused on wind turbine blades. For the computation domain part, it is suppressed because it is not counted in the carried-out meshing. This is because the structural analysis was only carried out on the turbine blades. Meshing FEA has the same function, which is inevitable in the analysis process. Without the meshing process, structural analysis cannot be carried out. In this study, the wind turbine blades included mesh sizes of 25 mm, 20 mm, and 18 mm. The simulation test results showed similar values for meshing sizes of 20 mm and 18 mm, but the meshing size of 18 mm provided a longer simulation time. The error percentages of 20 mm and 18 mm reached 0.98%. At a size of 25 mm, the trial simulation results generated a different value with an error percentage of up to 1.05% with a size of 20 mm. Therefore, this study used a mesh size of 20 mm. The meshing size results in a total of 36,130 elements and 72,974 nodes, as shown in Figure 5.

Fig. 5. VAWT Blade Meshing

2.3.3 FEA boundary conditions

The turbine boundary conditions were determined by inputting wind speeds of 3 m/s, 4 m/s, 5 m/s, and 6 m/s. The speeds were included in the boundary conditions of the static structure. In CFD modeling, the boundary conditions can be a sort of fluid, which in the placement requires inlet velocity and outlet pressure; accordingly, in FEA modeling, the boundary conditions are fixed support and imported pressure. The two boundary conditions must be set to fit. Fixed support was given to the blade center as the center of rotation, while imported pressure was on the third side of the wind turbine blades. The boundary conditions can be seen in Figure 6.



(a) **(b)**

Fig. 6. FEA Boundary Condition of VAWT Blade for (a) Fixed Support on Turbine, and (b) Pressure on The Turbine

2.4 Data Collection

Data collection was done after the simulation process. The simulation data greatly determined the drawn conclusions. Data collection was carried out based on the simulation results available in the post-process results of FEA modeling. The displayed data are total deformation, equivalent (von Mises) stress, and safety factor. The three data points were taken after simulating each material at different speed variations.

3. Results and Discussion

3.1 Total Deformation

Figure 7 shows the simulation results of the total deformation of the Savonius type vertical axis wind turbine blades at various wind speeds. The deformation results consist of three materials, i.e., Aluminum (Al), Stainless Steel (SS), and Fiberglass (FG). The tip of the blade provided greater deformation.

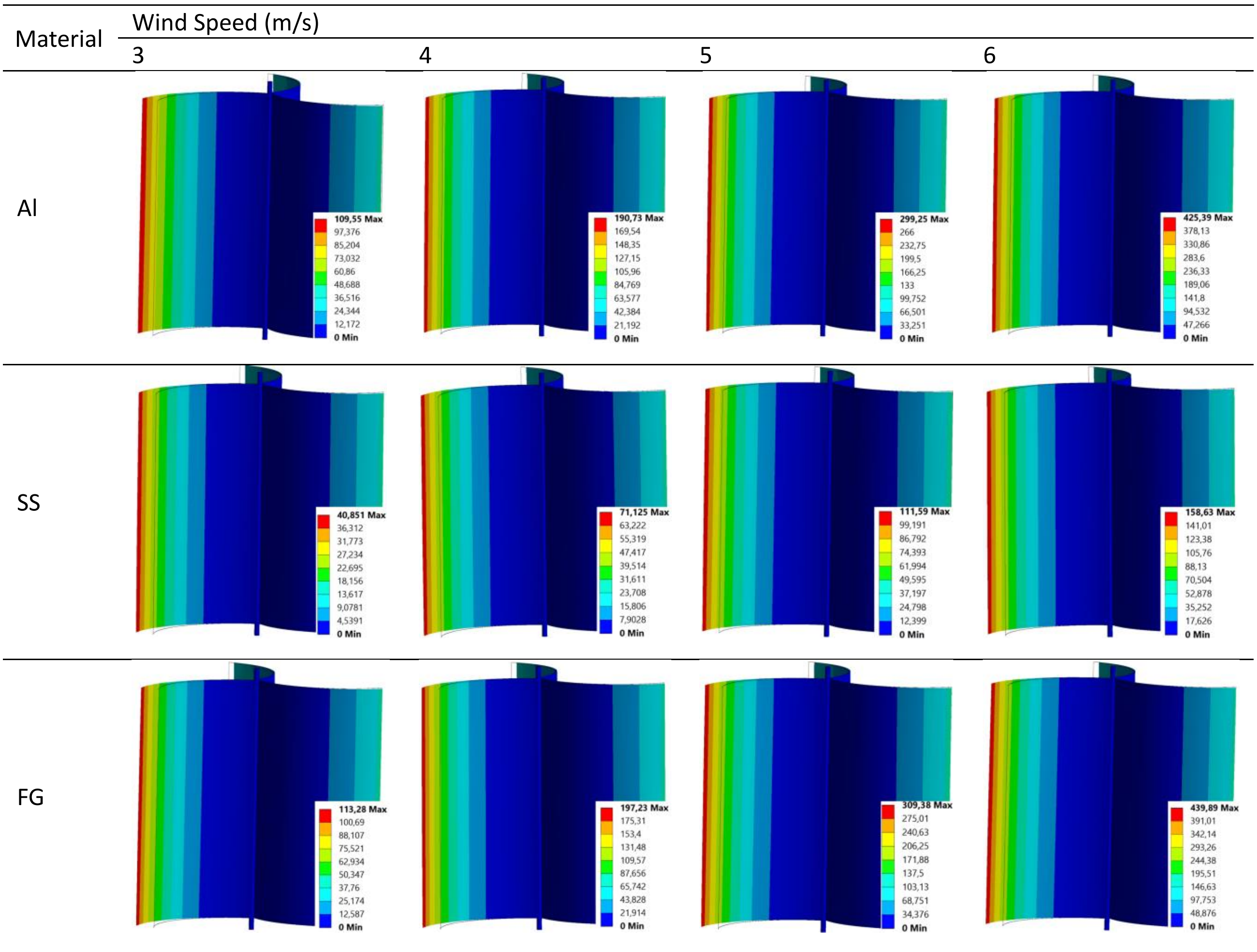


Fig. 7. Total Deformation on the Turbine Blades at Various Wind Speeds and Materials

Figure 8 presents the deformation values of the three materials. The deformation value is a number indicating the occurrence of a change in the structure's shape. The shape change determines the performance of the wind turbine. The recommended material has a lower deformation value. The deformation value is affected by the density of the material; higher-density materials encounter lower deformation. Deformation also depends on the loading experienced by the material.

Given a load at varied speeds of 3 m/s, 4 m/s, 5 m/s, and 6 m/s, aluminum and fiberglass experienced relatively high total deformation. Aluminum deformed at 109.55 mm at a speed of 3 m/s, 190.73 mm at a speed of 4 m/s, 299.25 mm at a speed of 5 m/s, and 425.39 mm at a speed of 6 m/s, respectively. As fiberglass experienced total deformation of 113.28 mm at 3 m/s, 197.23 mm at 4 m/s, 309.28 mm at 5 m/s, and 439.39 mm at 6 m/s. These similar conditions were obtained due to the almost similar densities of the two materials, about 2.77 x 10^{-6} kg/mm^3 and 2.6 x 10^{-6} kg/mm^3, respectively. Considering the total deformation results, aluminum, and fiberglass materials with a thickness of 3 mm are recommended to be used for wind turbines with lower speeds.

Stainless steel material generated the best and lowest values of total deformation results. This material had a total deformation value of 40.851 mm, 71.125 mm, 111.59 mm, and 158.63 mm at loading speeds of 3 m/s, 4 m/s, 5 m/s, and 6 m/s, respectively. Presumably, it was determined by the high-density value of stainless steel of about 7.75 x 10^{-6} kg/mm^3. The density of stainless steel is much higher than that of aluminum and fiberglass. With a low total deformation value, stainless steel can also be used in the production of vertical axis wind turbine blades. Based on the total deformation graph of the three materials at each speed variation, it is revealed that higher wind speeds generated greater deformation received by the turbine. It was in accordance with previous research on wind turbines [13].

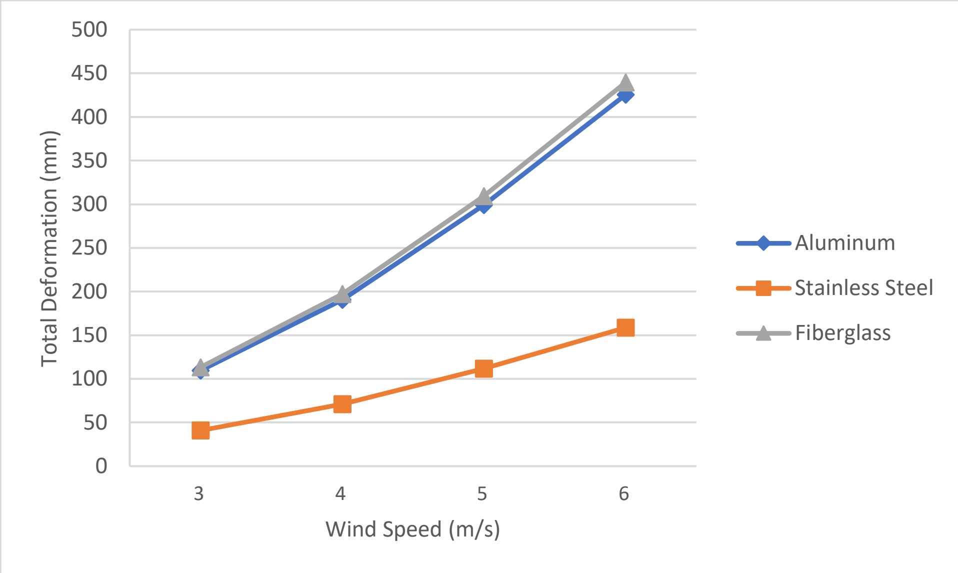


Fig. 8. Effect of Wind Speed on Total Turbine Deformation at Various Materials

3.2 Equivalent (Von Mises) Stress

Figure 9 shows the simulation results of equivalent (von Mises) stress on the turbine blades. This study investigated the loading of each wind speed variation for three blade materials, i.e., Aluminum (Al), Stainless Steel (SS), and Fiberglass (FG). The results showed that the dominant blade reaction was in the turbine blade basin.

Figure 10 shows a graph of the equivalent stress simulation results. The same loading was provided to each material, while the obtained value was proportional to the given loading. The presence of equivalent stress received by the component determined the safety factor value. Equivalent stress allows structural stress to be displayed in one plot. Equivalent stress, or von Mises stress, can be used as a scalar indicator to determine material failure. Finite element analysis on the Savonius type vertical axis wind turbine also obtained equivalent stress values to determine the magnitude of the stress received by the turbine blades. Aluminum material experienced equivalent stress values of 63.566 MPa, 111.26 MPa, 178.95 MPa, and 246.74 MPa, while stainless steel material obtained equivalent stress values of 63.831 MPa, 111.74 MPa, 180.99 MPa, and 247.77 MPa. Furthermore, fiberglass material had a stress of 64.672 MPa, 113.25 MPa, 189.84 MPa, and 250.92 MPa. Referring to the graph, it was revealed that an increase in flow velocity resulted in an increase in von Mises stress. This finding was agreed upon by the study conducted by Appadurai and Raj [24].

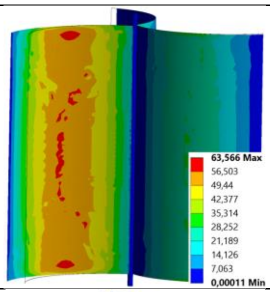
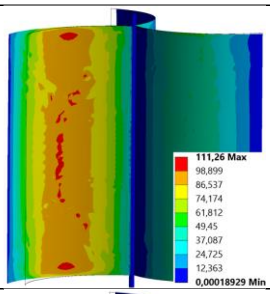
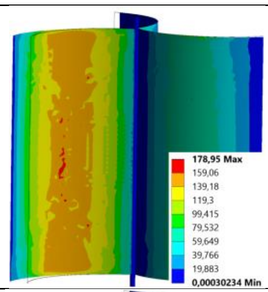
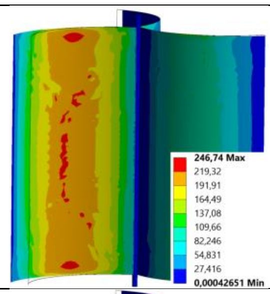
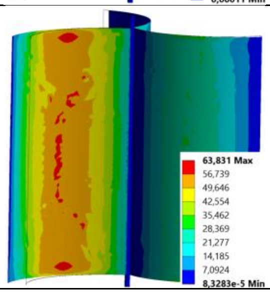
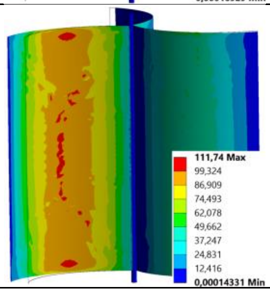
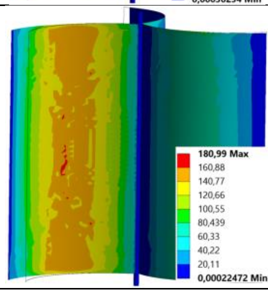
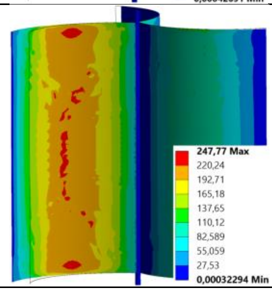
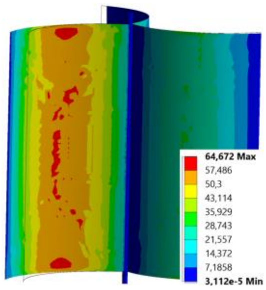
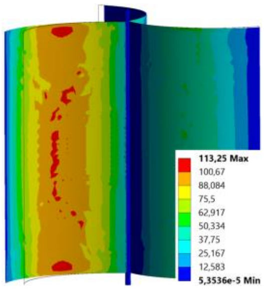
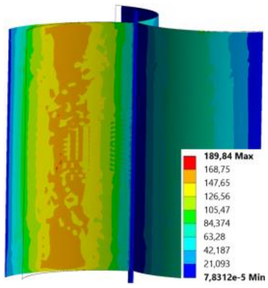
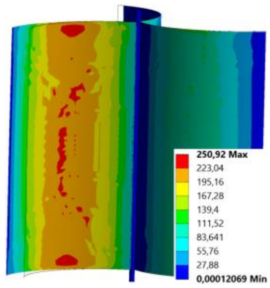
Material	Wind Speed (m/s) 3	4	5	6
Al				
SS				
FG				

Fig. 9. Equivalent (Von Mises) Stress on Turbine Blades at Various Wind Speeds and Materials

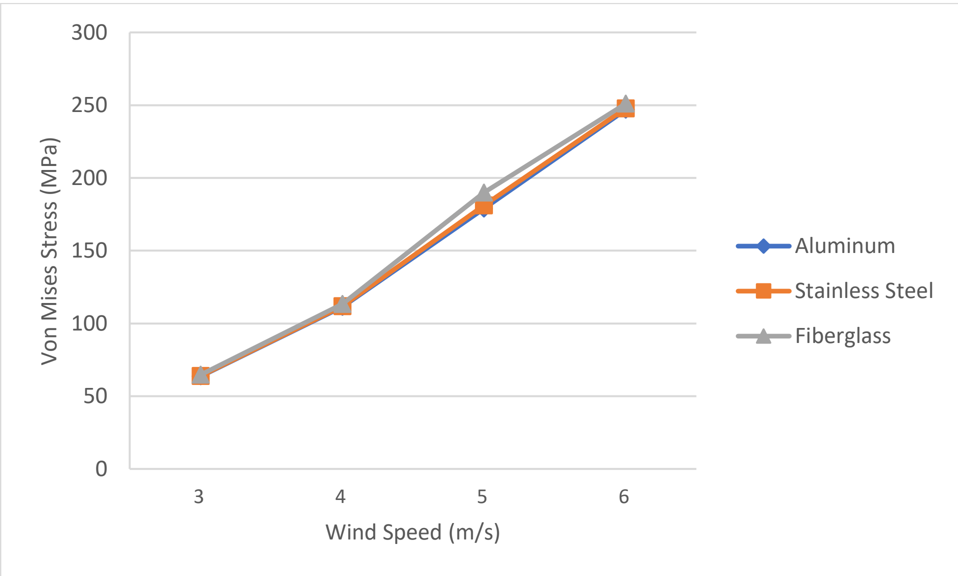


Fig. 10. Effect of Wind Speed on Von Mises Stress at Various Turbine Blade Materials

3.3 Safety Factor

Figure 11 shows the results of the safety factor simulation from the analysis of turbine blades. The safety factor indicates the strength of the material to withstand structural failure. It is shown that some parts were very safe, while others had the potential for structural failure.

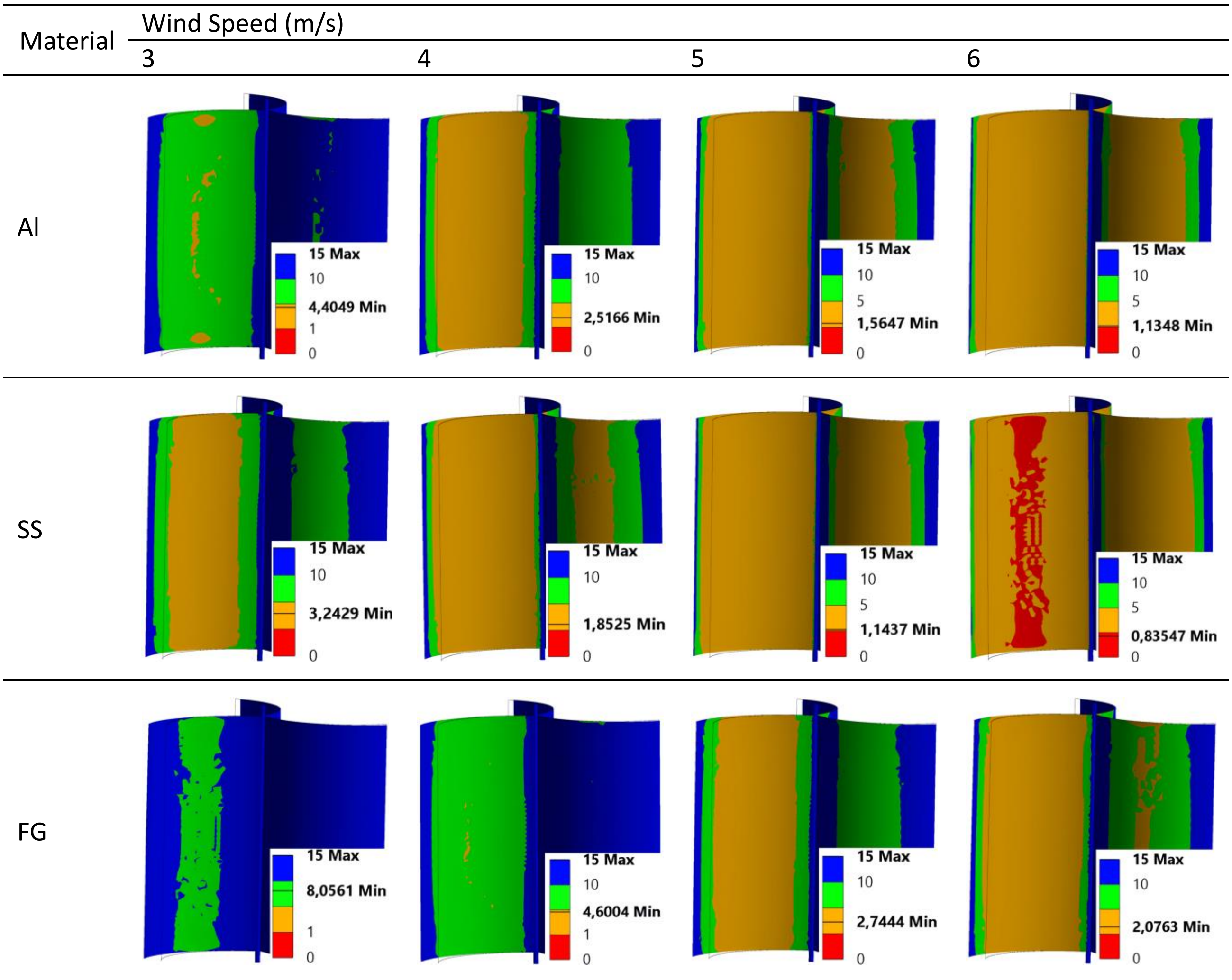


Fig. 11. Safety Factor on Turbine Blades at Various Wind Speeds and Materials

Figure 12 represents a graph of the safety factor value for each material with a given loading. Based on the graph, it is stated that the safety factor decreased with the increase in wind speed. It was indicated that the safety factor of aluminum blades at each loading was 4.4049, 2.5166, 1.5647, and 1.1348, respectively. Stainless steel material achieved safety factor values of 3.2429, 1.8525, 1.1437, and 0.83547. As for the fiberglass material, the obtained safety factors were 8.0561, 4.6004, 2.7444, and 2.0763. Among the materials tested, for each wind speed loading, only stainless-steel materials experienced structural failure at a wind speed of 6 m/s. A material achieving a safety factor value <1 indicates that the material experiences structural failure. In contrast to the von Mises stress, the safety factor is affected by the magnitude of the wind speed. When the wind turbine blades are given a low wind speed, the material will be far from the failure of the structure with a large safety factor value. On the contrary, at high wind speeds, the safety factor value is smaller while the failure rate of the turbine blade structure is greater. These results are in accordance with research conducted by D. Kumar and Sarkar [37].

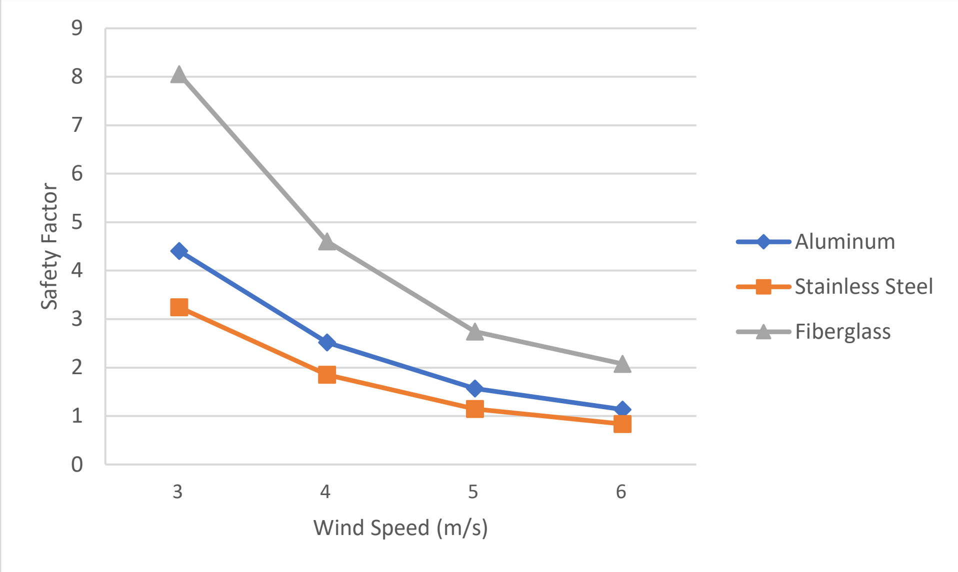


Fig. 12. Effect of Wind Speed on Safety Factor at Various Turbine Blade Materials

4. Conclusions

The mechanical properties of Savonius type vertical axis wind turbine blades in terms of deformation, equivalent (von Mises) stress, and safety factor have been studied at various loads of wind speeds, and types of blade materials. The findings provided valuable information for designing turbine blades. As one of the most important components of a wind turbine, its failure can disrupt the operation of the turbine. The results showed that wind speed loads had a significant impact on the mechanical properties of turbine blades. The higher the density of the material, the lower the total deformation of the turbine blades. However, the material used must also be sufficiently ductile to maintain the von Mises stress value below its yield strength. Under the investigated conditions, aluminum-based turbine blades gave promising results and were most recommended for use in the manufacture of Savonius type vertical axis wind turbine blades. Moreover, the material is beneficial in having a relatively cheap price, being lightweight, having corrosion resistance, and having sufficient durability because it provided safety factor values greater than one for all wind speed loads studied.

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