Energy Engineering
DOI:10.32604/EE.2020.011304
Article

Tech Science Press

Evaluation of Small Wind Turbine Blades with Uni-Vinyl Foam Alignments Using Static Structural Analysis

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Received: 30 April 2020; Accepted: 25 June 2020

Abstract: Mechanical characteristics of small wind turbine blades of National Advisory Committee for Aeronautics (NACA) 63-415 series with different Uni-vinyl (UV) foam alignments have been evaluated experimentally using Universal Testing Machine and numerically using Finite Element Analysis (FEA) software ANSYS. The wind turbine blade models considered are selected from the NACA 63415 series to give a power output of 1 kW. The blades in this study are made like a sandwich beam structure. The outermost portion of the blade is made of glass fiber reinforced plastics with epoxy resin as composite and Uni-vinyl foam alignments are placed in the inner portion, which acts as a stiffener. The alignments used in the blades are rectangular, taper, and teardrop. In FEA analysis, the load is converted into equivalent wind force and applied to the blade structure. Deformation and stress distributions are evaluated at different locations of the blade under different loading conditions. It is observed that the blade with teardrop alignment is having more resistance towards bending compared to blades with other alignments. It is also observed that the taper alignment blade is more capable of sustaining higher stresses as compared to the solid and hollow blades.

Keywords: NACA 63415; uni-vinyl foam alignments; small wind turbine blade; static structural analysis

1 Introduction

In the present scenario, there is the utmost importance and demand for clean electricity because of the boom in the power sector and the wind turbine market. The wind turbine systems with small blades are suitable for producing electricity for household purposes. The wind turbine blades made of lightweight composite materials are having adequate structural strength. Therefore, the wind turbines blades are a crucial part of harnessing the wind energy and requiring improvements for effective energy conversion to suitable forms. In wind turbines, the energy conversion is achieved by first converting linear velocity of wind into rotary motion using mechanical equipment and then converting rotational mechanical energy into an electrical form using an alternator or a generator. Here, the extracted kinetic energy of wind is converted into a rotary form and resulted in the motion of blades. It means that the blades can be exerted aerodynamic forces on them to cause their rotation.

Kim et al. [1] studied the characteristics of 750 kW capacity wind turbine having composite blades using the static, dynamic, and modal tests. These tests were performed with fiber Bragg grating sensors, laser displacement sensors, and electric strain gauges. The fiber Bragg grating sensors were used to predict the structural behavior of the blade with respect to the concerned load. The electric stain gauges and laser displacement sensors were used to compare the deflections of blades. The dynamic characteristics of blades were also investigated by conducting a modal test with fiber Bragg grating sensors. It was found that fiber Bragg grating sensors have good potential to define the static and dynamic behavior characteristics of the composite blade. Yeh et al. [2] studied the characteristics of 5 MW wind turbine modal having blades of a sandwich structure. The blade is having its outer portion made of carbon fiber/epoxy composites and a stiffener made of PVC is placed at the inner core. The stress evaluation was done at 0° and 120° pitch angle and it was found that at 0° the stresses become smaller as the load gradually decreases. Still, the displacement and von-mises stresses are more at 120° angular position form its vertex. Imane et al. [3] evaluated the characteristics of small wind turbine blades. The deformations, lateral, twisting, and bending stresses were determined using a finite element method of discretizing the blade. The modal superposition method was also adopted to study the forced motions using aerodynamic loads. A mathematical model was used to calculate the life of the blade. Ioan Curtu et al. [4] evaluated the performance of NACA 44XX aerofoil shaped wind turbine blade with a length 1.5 m using a simulation method. Four types of external loads like gravitational, aerodynamic, operational, and gyroscopic forces were applied on a horizontal surface of the blade, as shown in Fig. 1. The maximum stress regions of the blade were identified to avoid the risk at the time of static and dynamic loading.

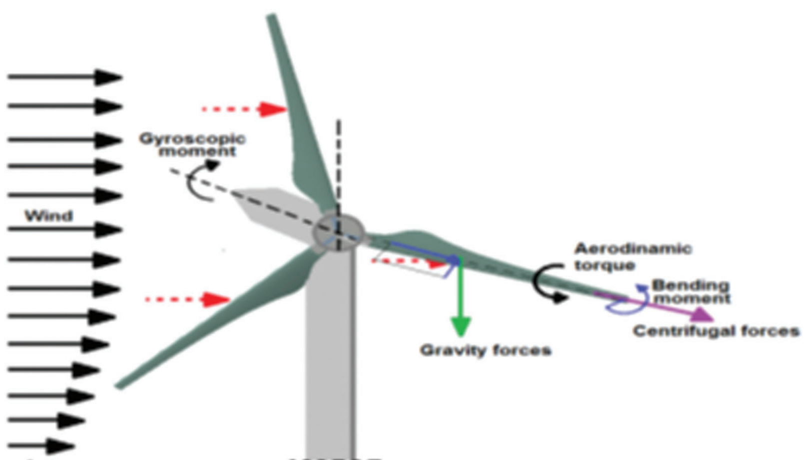

Figure 1: Various possible forces can act on blades [4]

Kumar et al. [5] studied the characteristics of small wind turbine blades and evaluated their mechanical properties using bend tests and tensile tests. The blades were manufactured from composites having a banana, sisal, and jute layers. It was observed that the blades made of banana and sisal composites give high tensile strength as compared to the blades made of Jute composites. Curtu et al. [6] designed various stages of a bench to test the wind turbine blades for five loading cases. The experimental and FEM analysis was conducted on blades. It was found that fixing the stand in both the foundations of the pillar was given considerably good results. Mathew et al. [7] investigated the turbine blades made of different materials like aluminium alloy, structural steel, and carbon alloys, etc. It was found that blades made of epoxy carbon were having good strength and hence they were suitable for windmills. Wang et al. [8]

studied the characteristics of the 3D model of the NACA0012 aerofoil blade using finite element analysis. It was found that the maximum stress is acting at the central portion of the blade. They also conducted a tensile test on blades made of GFRP composite material and found that the maximum displacement is taking place at the tip portion of the blade. Schubel et al. [9] studied design models of horizontal axis wind turbine blades, which include theoretical maximum efficiency, propulsion, practical efficiency, blade loads, gravitational, operational conditions, and provided a detailed review. Feng et al. [10] studied the performance of small turbine blades and evaluated static and dynamic characteristics using Finite Element Analysis. Tenguria et al. [11] evaluated the performance characteristics of the NACA 634-221 aerofoil wind turbine blade using Glauert's optimal rotor theory. The blade was designed with a length of 38.95 m for 1.65 MW of power production. The finite element analysis (FEA) was used to determine the relative web and cap deflections of the blade. It was observed that for the same loading conditions, the results obtained using the FEA approach and experimental method were very much similar with a slight change in the magnitudes of deflections. Song et al. [12] studied the optimal design of a 20 kW horizontal axis wind turbine blade of the NACA 63415 series. The Wilson method of the design process was considered to solve optimum calculations using the MATLAB program. The static analysis of the blade under static loading conditions was used for evaluating the deflections and stress distributions on the blade. Wang et al. [13] investigated the behavior of NACA 4412 series hollow wind turbine blades using finite element analysis. The blade model was fitted with a magnetorheological fluid (MRF) sandwich structure to obtain the power output of 750 kW. The mode shapes of these smart wind turbine blades were analyzed under various loading conditions with three MRF arrangement layouts at root, middle, and tip portions. It was found that the MRF sandwich structure must be arranged at the root of the blade for avoiding the torsional vibrations. Kumar et al. [14] evaluated the performance of hub design on a horizontal axis wind turbine blade. The hub made of spheroidal graphite cast iron (GGG 403) was replaced by aluminium alloy 6061(AA6061) and it was found that the mechanical properties of cast hub and the strength-to-weight ratio were improved. Pardo et al. [15] worked on structures of wind turbine blades particularly with a focus on a detailed evaluation of 2D model deflection. It was found that severe stresses and strains were occurring when the bending of blades take place and the non-linearity of the geometry of blade has become more critical with the increase of laminate thickness.

Benham et al. [16] worked on structural and modal analysis of the NACA 4412 profile-based wind turbine blade. The composite materials like E-Glass fiber, carbon fiber, S-Glass fiber, and Kevlar fiber is were taken for the fabrication of blades. The maximum lift to drag ratio of the profile was obtained at a five-degree angle of attack. From the analysis, it was observed that Kevlar fiber has minimum deformation and stress intensity as compared to other types of blades. Chou et al. [17] evaluated the critical wind loads and failure analysis of small wind turbines using structural mechanics simulations. The blades of 39.5 m length and 6.5 tons of weight were considered for analysis. For maximum resistance, a wind speed of 70 m/s was used to analyze the blade cracks, delaminations, and cover damages. Jensen et al. [18] investigated the structural strength and numerical simulation of 34 m composite wind turbine. By using nonlinear Finite element simulation, the local displacements were measured at the identified location where catastrophic failure was initiated. The comparison of relative cap and web deflections were made from the experimental and simulations analysis. At the blade section of 10.3 m, the imperfections in load carrying cap would expect to influence the local deformation behavior. Otero et al. [19] Worked on structural analysis of wind turbine blades by the Timoshenko beam model. A code was developed to full scale composite laminated blades and stress and vibrational modes were evaluated in normal operational conditions. The stiffness and inertia matrices were calculated and computed to the blade geometry. Veludurthi et al. [20] performed a comparative investigation using the modal and harmonic analysis of different blades like solid, hallow, and rectangular uni-vinyl foam alignment blades.

For all blades, the natural frequencies, mode shapes, and amplitudes were evaluated using the finite element and experimental analysis.

The main objective of this work is to develop the blades for small size horizontal axis wind turbine systems using a specific design methodology. NACA 63415 airfoil section is used to develop the wind turbine blades with glass fiber reinforced composite and resin as an epoxy. UV hard foam sandwich material acts as a stiffener and serves as a central beam in the blades. In this work, a total of five different varieties of blades like solid, Hollow, Hollow with rectangular alignment, Hollow with taper alignment, and Hollow with Teardrop alignment blades are developed for investigation. Structural analysis is carried out to determine the static behavior of the developed blade models. Further, an experimental investigation of load-deflection tests is also carried out done using a universal testing machine (UTM). Based on the results obtained from finite element analysis and experiments, a better blade model with good structural strength and high stiffness can be identified.

2 Finite Element Analysis

In this work, the strength capability of small wind turbine blades of five different varieties is carried out. The blades like solid, Hollow, Hollow with rectangular alignment, Hollow with taper alignment, and Hollow with Teardrop alignment are considered for investigation. These alignments act as a stiffener inside the Hollow blade. The blade and alignments are modelled using CATIA v20 and the analysis is carried out using Finite element analysis software ANSYS 18.1. The aerofoil section of the blade is designed using NACA 63-415 series sections along the length.

2.1 Modelling of the Wind Turbine Blade (Three-Dimensional Model)

The blade was designed first by selecting the aerofoil section. In this scenario, the three-dimensional coordinates of each aerofoil profile of different chord lengths from root to tip of blade are generated from the National Advisory Committee for Aeronautics 63415 series. The coordinates of three axes are taken into CATIA software and surface are created using surface sheet metal operation. The blade is designed for a swept area of 2200 mm and to produce 1 kW power output. The length of the blade is taken as 1100 mm along the aerofoil section and a three-dimensional model of the wind turbine blade is created as shown in Fig. 3. The 3D modelling of a wind turbine blade with different chord lengths at different sections is modelled and the blade area in two dimensions is evaluated as 139323.47 mm^2, as shown in Fig. 2. The stiffener ribs of various alignments like rectangular, taper and teardrop are optimized and

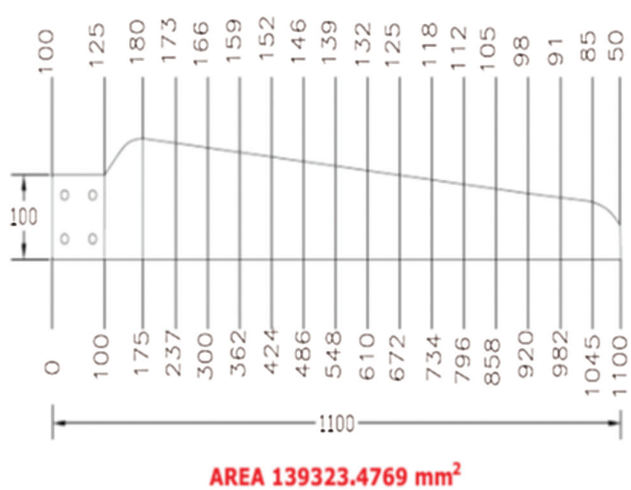

Figure 2: Two dimensional model of a small wind turbine (SWT) blade [20]

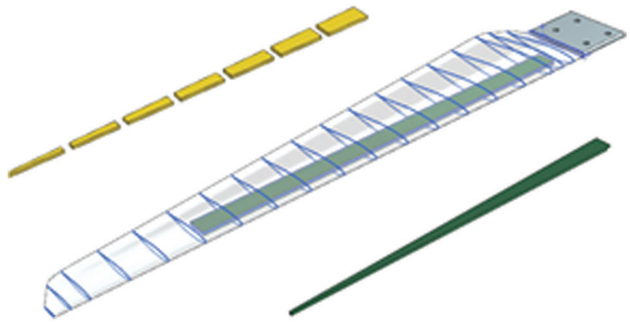

Figure 3: CAD model of a SWT blade with various alignments at inner core

inserted in the hollow section of the aerofoil wind turbine blade. The blade is operated under wind speed of max 12 m/s. The Reynolds number used is 5×10^5. Different types of wind turbine blades like solid, hollow, rectangular alignment, taper alignment, and teardrop alignment blades are modelled and converted to FEA models with an extension of dot dxf or dot igs files.

Table 1: Essential input material properties for pre-processing [20]

Sl. No	Material used	Modulus of elasticity E (N/mm^2)	Poisson ratio	Density (Kg/m^3)	Yield strength (N/mm^2)
1.	GFRP + Epoxy	1.8×10^4	0.28	1800	265
2.	UV Foam	8632.8	0.24	320	–

2.2 Analysis of Wind Turbine Blade Model

The aero-mechanical performance of a small wind turbine blade with a horizontal axis can be evaluated by taking the wind forces as input data. The blade deflections and stress distribution on the wind turbine blade can be estimated using this data. In blades, load up to a maximum of 800 N is considered for analysis as shown in Figs. 4 and 5. The deformation and stresses of the solid blade are evaluated when maximum load acts at the tip. A similar analysis is also performed for the remaining five different blades by increasing the wind forces at the blade tip.

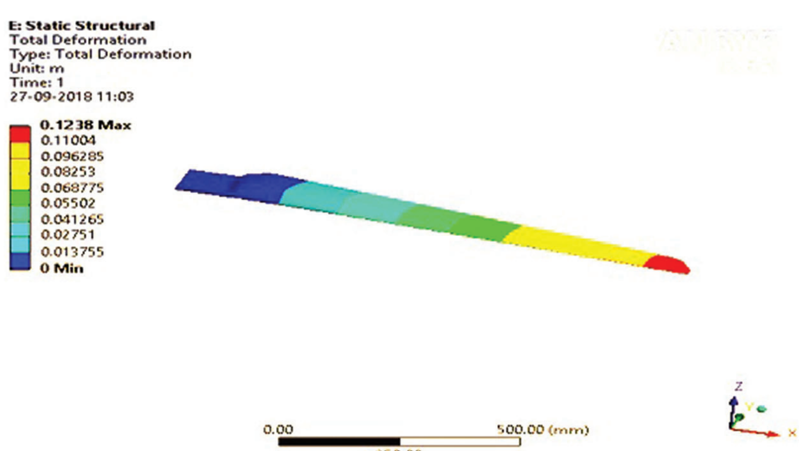

Figure 4: Total deformation of SWT Blade loaded at the tip

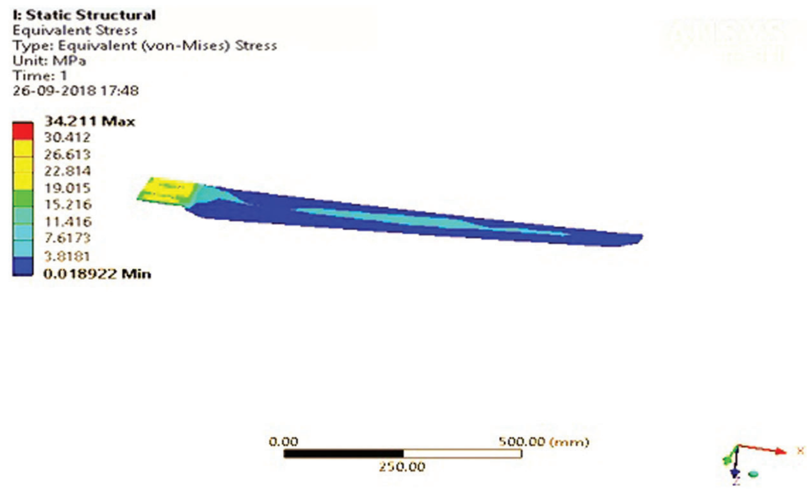

Figure 5: Stress distribution of SWT blade loaded at the tip

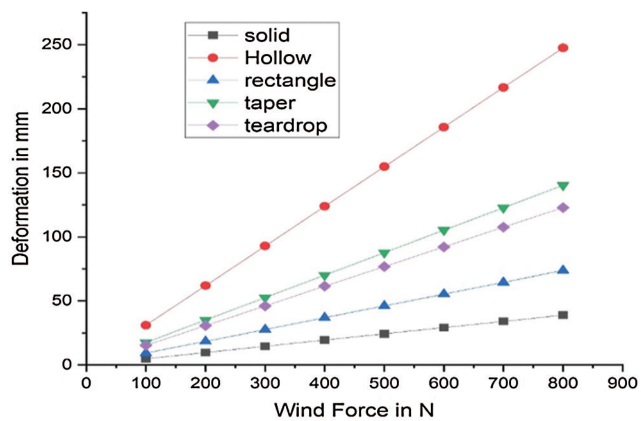

Figure 6: Variation of deformation with respect to wind force on different blades

The graphs for variation of deformation and stress as functions of wind pressure are obtained for all types of blades as shown in Figs. 6 and 7. For solid blade, the deflections and stresses are low compared to other varieties of blades, whereas the stresses are very high in taper alignment blade and deflections are more in the hollow blade. It can be observed from graphs that the rectangular alignment blade is giving an acceptable value of the yield strength below 265 N/mm^2 and the taper alignment blade gives an optimized. The value that is slightly higher compared to solid, hollow, rectangle and taper drop alignments.

3 Fabrication Wind Turbine Blade

The small wind turbine model is adopted from the 1 kW model of the NACA 63415. The model is made for a length of 1100 mm using 21 aerofoil sections. The rectangular part at the root section is connected to the hub. The blade is composed of two skin halves of the upper and lower portions. The blade is made of a sandwich structure consisting of biaxial glass fabric reinforced polymers (GFRP) matt along with different stiffener alignments of Uni-vinyl foam. The stiffener is placed inside the blade for improving the strength. The stacking sequence of GFRP composite material has [0°/45°/90°] to make four layers in both upper and lower parts. The Epoxy resin mixed with hardener is used as an adhesive bonding element for the fibers. The different stiffness ribs of Uni-vinyl alignment like rectangular, taper and teardrop are placed in the down portion of the wind blade to increase the strength of the sandwiched wind blade as shown in Fig. 8.

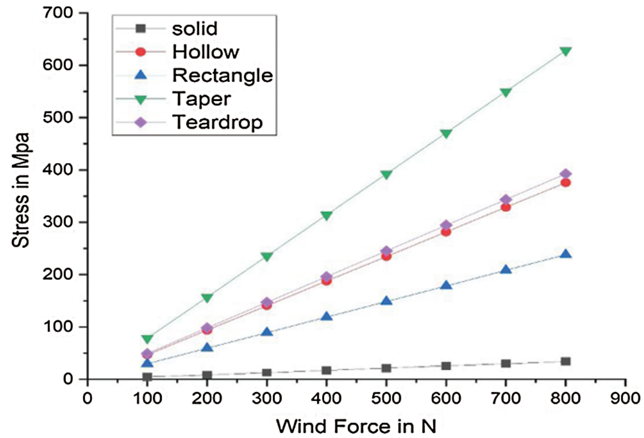

Figure 7: Stress variation at different wind forces on different blades

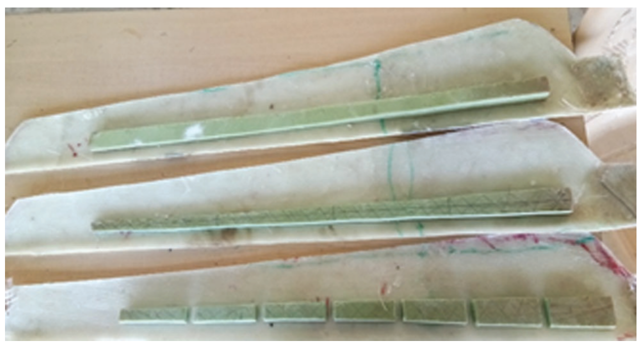

Figure 8: Different blade alignments placed in downside portion of blade

Table 2: Details of fabricated blades

S. No	Materials	Alignment	Blade Type	Blade Weight (Kg)
1.	GFRP + Epoxy	–	Solid Blade	2.850
2.	GFRP + Epoxy	–	Hollow Blade (without stiffener)	1.64
3.	GFRP + Epoxy	Rectangular	Hollow Blade with Rectangular alignment as a stiffener	1.990
4.	GFRP + Epoxy	Taper	Hollow Blade with Taper alignment as a stiffener	1.852
5.	GFRP + Epoxy	Teardrop	Hollow Blade with Teardrop alignment as a stiffener	1.775

After closing the blade with second-half, i.e., on the opposite side of the blade accurately, the two pieces are in proper alignment. They are cured at room temperature for 20 hours. The unfinished blade is taken for different processes like blade trimming, bluffing, and finishing using emery paper. The first coat of paint is done on the blade and the final coat of paint is done after conducting the weight balancing test with the rotor, as shown in Fig. 9. The complete procedure of fabrication of the blade is done by hand lay-up technique.

Figure 9: Fabricated model of NACA 63415 aerofoil blade

4 Experimental Procedure and Discussion

In the experimental part of this work, the load-deflection tests are conducted on small wind turbine blades of all alignment models (i.e., Solid blade, hollow blade, rectangle alignment blade, taper alignment blade, and teardrop alignment blade) to determine their ultimate strength. A well-designed standard fixture is used to hold the blade at the root section and it resembles a cantilever beam. At the tip section of the blade, the load is applied with small increments. This experiment is carried out by applying the point load at the tip of the blade and the related deflections are measured at three locations of the tip, mid and root sections. The experimental setup after placing the blade in the universal testing machine (UTM) is shown in Fig. 10. During the loading of blades, the magnitude of the load increased, and blade deflections are measured using dial indicators arranged at different locations, and also corresponding deflections count is recorded. The load is applied until the failure of the blade occurs. One large size crack that occurred at the root section due to loading is shown in Figs. 11 and 12.

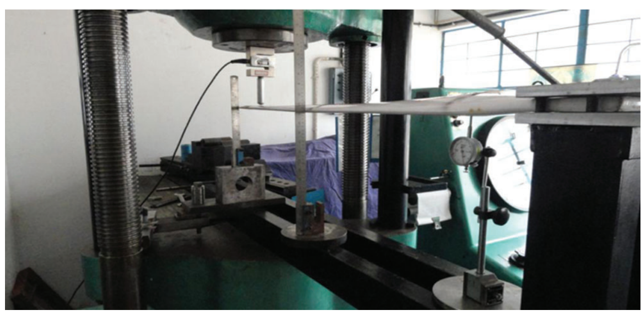

Figure 10: Load deflection test setup used when load is applied at tip of fabricated blade

Figure 11: Crack occurred at root portion of solid blade (side view)

Given experiments, it is difficult to apply the load in the form of wind pressure because the nature of wind cannot be applied as its nature differs dynamically. The structural testing blades by application of concentrated load and the deformations identified at crucial locations has been the standard method for the acceptance of the blades to fit into the assembly of wind turbines and its use in power production.

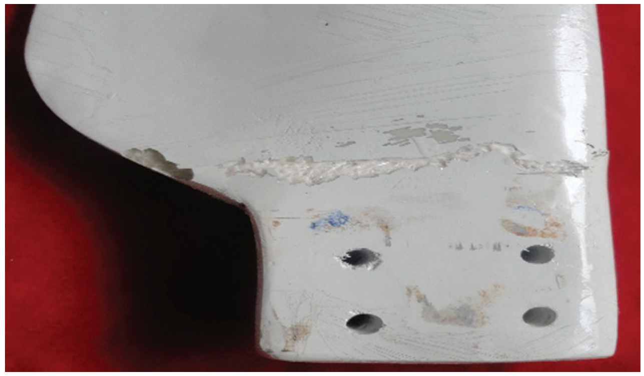

Figure 12: Crack occurred at root portion of rectangle alignment blade (top view)

The total deflection of the blades is measured at different locations to the given loading conditions. The results obtained are shown in Figs. 13–17. It is observed that when the given varieties of blades are subjected to different loads at point locations, the failure crack occurs mostly at the root section of the blade and tends to fail by creating crackling sound. It can also be observed that the blades with teardrop alignment can carry the maximum load (i.e., 77 kg) and the hollow blades can carry the least load of

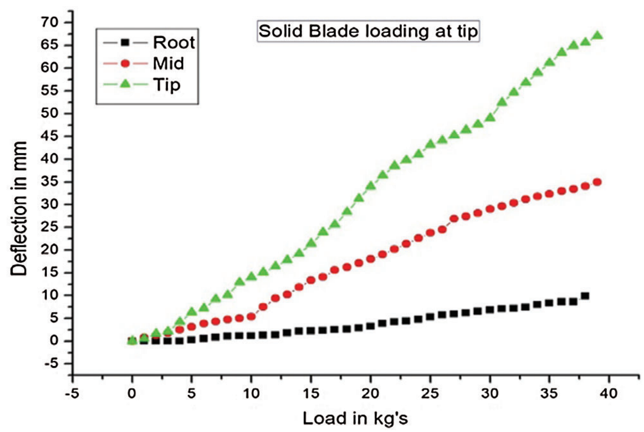

Figure 13: Load deflection test results for R-22-Solid blade

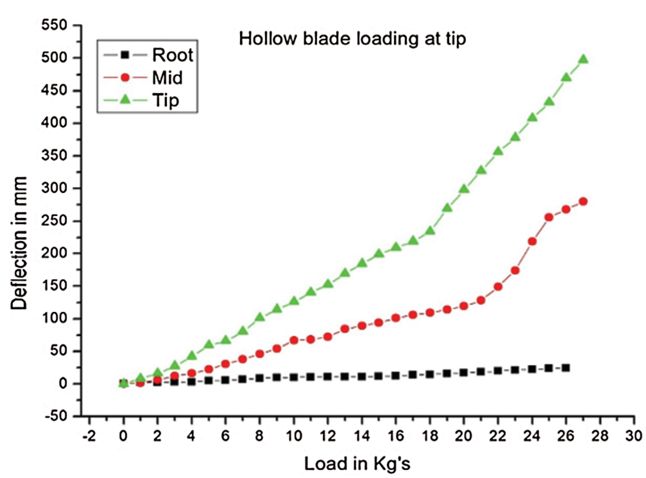

Figure 14: Load deflection test results for R-22-Hollow blade

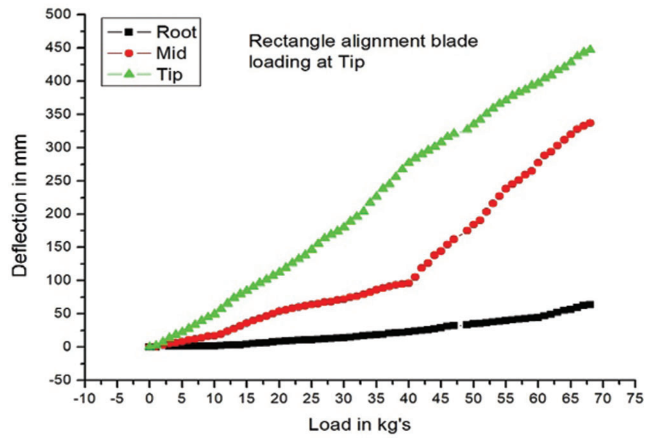

Figure 15: Load deflection test results for R-22-Rectangular alignment blade

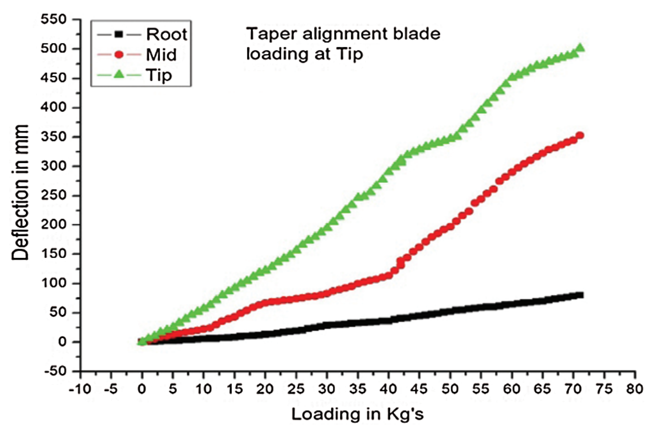

Figure 16: Load deflection test results for R-22-Taper alignment blade

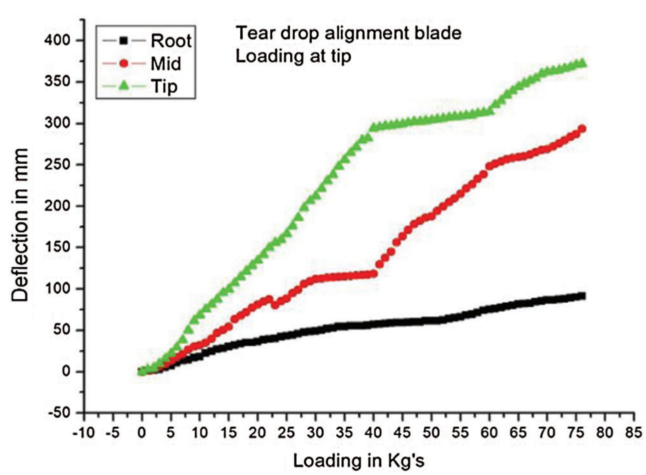

Figure 17: Load deflection test results for R-22-Teardrop alignment blade

27 kg as shown in Figs. 14 and 17, respectively. It can also be observed that the deflections are maximum for teardrop alignment blades and minimum for solid blades (See Figs. 13 and 17).

5 Conclusions

The performance of a solid blade, Hollow blade, and Hollow with three different Uni-vinyl foam alignments as stiffeners is analyzed. Stress distribution and deformation at various loads are determined using finite element analysis and the deflections are determined experimentally using the UTM. The following conclusions can be made from this work.

- When wind forces are applied as the load on different blades, it is observed that the blades with teardrop alignment and rectangular alignment have undergone less deformation of 61.45 mm and 36 mm, respectively. The stresses obtained for these both alignments are found to be 196.31 N/mm^2 and 119.32 N/mm^2, respectively, which are considered not exceeding the limit of yield strength.
- Taper alignment blade can sustain the higher stress of 714 N/mm^2 while failure occurred in the solid and hollow blades at less stress values of 35 N/mm^2 and 385 N/mm^2, respectively.
- For teardrop alignment blades, the deflection is almost linearly increased up to 40 kg load, and the rate of increase in deflection is quite low from 40–60 kg load. Finally, cracks occurred at 77 kg load leading to failure of the blade.
- It is observed that in teardrop alignment blades, the use of teardrop stiffener ribs has improved the flexibility and rigidity of blades to resist the bending moment of the blade as compared to all other varieties of blades.

Acknowledgement: The authors are thankful to the Vellore Institute of Technology (VIT), Vellore, Tamilnadu, India, for its extended support in using the facilities available at VIT.

Funding Statement: The author(s) received no specific funding for this study.

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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