Arid Zone Journal of Engineering, Technology and Environment, June, 2017; Vol. 13(3):315-324
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Print ISSN: 1596-2490, Electronic ISSN: 2545-5818, www.azojete.com.ng

INVESTIGATING THE SUITABILITY OF SELECTED STRUCTURAL MATERIAL FOR THE BLADE OF AN HORIZONTAL AXIS WIND TURBINE

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Abstract
This work presents a comparative analysis on the structural material of a blade used for the horizontal axis wind turbine, which was based on previously developed blade geometry. Two blades of the same parameter: 0.25 m chord lengths at 8 ^{o} angle of attack, but different structural materials were compared. This to identify an optimized blade structural material in terms of locally available, strength, cost effectiveness and environmental safety that will be suitable for Maiduguri's weather condition. The ultimate flap - and edge - wise deflections and load conditions under minimum blade mass (6.8 kg) are determined. These investigations were carried out in two stages: predictions of the aerodynamic analysis using Computational Fluid Dynamics (CFD) code (ANSYS Fluent CFD commercial tool) with Blade Element Momentum (BEM) theory, Finite Element Method (FEM) coded in MATLAB software for the structural analysis and experimental evaluations for the purpose of validation of predicted data obtained. These were employed in order to provide sufficient conclusions of the aerodynamic and structural data that will provide better performance of the blade. These data are expected to handle the design variables meant for the optimization of the blade based on the selected structural material. The blades of each material were divided into 15 elements along the blade span with each element assumed to have uniform cross sectional area. Pressure distribution within the computational domain and around the airfoil section in two dimensions (2D) was predicted. The validated results of the load to deflection showed good agreement and that each of the blade material were based on the structural strength. From the result obtained, it shows that the aluminium blade structure material has good reliability with better performance. These were significant between the maximum strength and the minimum blade mass for aerodynamic loadings, hence better blade structure than that developed from beach wood and most suitable under an ultimate wind speed of 30 m/s.

Keywords: Aerodynamic analysis, blade structural materials, lift and drag forces, flap - and edge - wise deflections

1. Introduction

Horizontal Axis Wind Turbine (HAWT) is the most common type of wind turbines used for extracting kinetic energy from wind, is a type of wind turbine that has wind flowing along the axis of rotation of its rotor. The component of the turbine that extract this energy, is the rotor's blade and thus requires the use of optimum material that can endure aerodynamic, gravitational, inertia and operating loads (Domnica *et al*., 2016, Gujicic *et al*., 2010). Although structural analysis has always been a significant factor in the blade design of wind turbine and is mainly because of fatigue issues, but critically the structural material should be a concern that should not be ignored (Zhu *et al*., 2016). In addition, as the turbine blade operates in a wide range of wind conditions, its optimization would be better enhanced by considering the structural material (Cai *et al*., 2012, Babu, 2006, Domnica *et al*., 2016). One of the major causes of failure in HAWT is the excessive deflection from the root to the blade tip, which is called flap - wise bending and is due to high pressure exerted on it by the wind. If the structure of the HAWT is unable to withstand the exerted high wind pressure, even though depending on the blade structural material, the blade will be deflected beyond the clearance of the tower and the rotor. This could result into collision of the blade with the HAWT tower, which could also be the results in total failure of the system.

Several investigations have been conducted relevant to blade structural materials over the years, but never the less the facts still remain that blade structural material should be of high stiffness, low density, largely available with cost effectiveness and long fatigue life (Supeni *et al*., 2012). In reality, investigating the blade structural material is a difficult and expensive task, but by limiting the investigative techniques capable of attaining realistic predictions, the research could be attainable. This could significantly help in reducing cost as computational efforts are reduced and hence the current investigative trend is feasible. The use of Reynolds-averaged Navier-Stokes (RANS) models or other viscous - flow codes could be applied in 2D geometrical model to determine the best airfoil and loads along the blade span (Masson *et al*., 2001, Junadi *et al*., 2016).

The basic aspects of blade structure design are the selection of material and shape. Even though the material selected for the turbine blade, should be of high strength in order to maintain optimal shape and performance, low density to reduce gravitational forces and long - fatigue life to reduce material degradation (Chen *et al*., 2014, Zhu *et al*., 2016). The materials predominantly used for blade structure are composites (glass or carbon fiber with proxy resin), but these are either expensive or not readily available in many developing countries typically Nigeria. These materials are also non - bio - degradable, non - recyclable and have health hazards (Babu, 2006). Therefore it requires that other similar materials of significant characteristics which can also withstand wide range of wind flow pattern can also be considered. However, the wind flow pattern in Nigeria, specifically Maiduguri of North Eastern part of the country is characterized by high wind speed fluctuations, which are mostly recorded during transitional and raining seasons. Maiduguri's annual average wind speed is 4.89 m/s at 10 meter above ground level and wind speeds of 20 to 30 m/s should be anticipated (Ngala *et al*., 2016, Shuwa *et al*., 2016). The wind of such magnitude will be expected to exert high pressure on the blade and a wind speed of 30 m/s is considered as the ultimate wind speed for the current work.

The present work concentrate on using two locally available HAWT blade structural materials these are: aluminum and beach wood, the materials were selected based on their availability and lightness in weight. These materials will be numerically analyzed as blade using Blade Element Momentum (BEM) and ANSYS Fluent CFD code, it will also be analyzed experimentally using a simple cantilever testing rig. These are expected to reveal the best and optimum HAWT blade structural material suitable for Maiduguri wind condition. National Adversary Committee on Aeronautics (NACA) 4419 blade geometry which was developed by Ngala *et al*., (2016) and Shuwa *et al*., (2016) for Maiduguri was adopted for the present investigation. Experimentally, each of the blades was subjected to flap - wise and edge - wise loading conditions as well as the deflection caused by the loads using a dial indicator at 15 points along the blade span (0 to 1.5 m at interval of 0.10 m).

2. The Research Methodology

2.1 Material Selection

The materials used in this work were selected based on the local availability, strength, cost effectiveness and environmental safety of the materials. Also considered in the selection are strength to weight factor, environmental compliance and review of previous work. The mechanical properties of the two materials were also identified and the two blade structural materials considered for the current comparative and selection analysis are aluminium and beach wood. CFD and experimental analysis of the two structural materials were carried out in order to know the ability of the materials for resistance under loading deflection.

Aluminium is a silvery white metal with a density of 2770 kg/m^3 (Junadi *et al*., 2016), about a third that of steel and was considered because it was found to have a lower fatigue level, lightweight and less stiff than steel. Aluminium is ductile, good heat conductor and cost effective metal with good reliability and strength. Beach wood is a cellulose and lignin material with a density of 630 kg/m^3 and is found in many engineering applications, which have long been a common construction material. Woods are potentially interesting because of their low density, but are rather low in stiffness, which makes it difficult to limit the deflections (elastic) for very large rotor blades. Furthermore, wood is a natural material and thus environmentally attractive and can be obtained in reproducible and high quality, which is a requirement for a stable and economical requirement for the manufacturing of rotor blades and thus economically attractive (Babu, 2006).

2.2 Simulation Procedure

The HAWT blade geometry adopted for this comparative analysis was based on the blade developed by Ngala *et al*., (2016) and Shuwa *et al*., (2016) for Maiduguri environment. This blade is further simulated under an ultimate wind speed of 30 m/s using ANSYS Fluent CFD code to determine the maximum lift and drag forces acting on the blade. The lift and drag forces are given by Equation 1 and 2, respectively.

$$F_L = \frac{1}{2}\rho v_{ulti}^2 CLC_L \tag{1}$$

$$F_D = \frac{1}{2}\rho v_{ulti}^2 CLC_D \tag{2}$$

$$x_{L(0\to x)} = \frac{F_L}{AE}\int_0^L LdL \tag{3}$$

$$x_{D(0\to x)} = \frac{F_D}{AE}\int_0^L LdL \tag{4}$$

The deflection (x_D) of the blade structural material with drag force (F_D) is obtained from Equation 5

Where: ρ is the density of air (1.225 kg/m^3), v_{ulti} is the ultimate wind speed (30 m/s), C is the chord length of the blade, L is the blade span, C_L and C_D are the coefficient of lift and drag and are assigned 1.238 and 0.0101, respectively, from design foil workshop code at 8 ^{o} angle of attack.

To determine the flap and edge - wise deflections (x) of the blade based on wind pressure caused by the ultimate wind speed, lift and drag forces in Equations 1 and 2 are applied in Equations 3 and 4.

In carrying out the comparative analysis, two blades were geometrically created from the structural materials and are of the same blade geometry. Since the blade has one end fixed (root) and the other free (tip), it is considered as a cantilever subjected to uniformly distributed load.

Finite Element Method (FEM) and MATLAB were used to determine the deflection of each 1.5 m model blades. The span is divided into 15 elements and the deflection of each element was determined for flap and edge - wise conditions, as Figure 1 (schematic) and 2 (experiment) shows.

Generally the deflection, x as in Equation 5, of the blade from its natural axis when subjected to uniformly distributed load, P was determined from Equation 1 using Finite Element Method and MATLAB. The blade structure is discretized into 15 elements and the deflection of each element as a result of centrifugal, lift and drag forces determined using the MATLAB tool.

$$x = \frac{PL}{AE} \tag{5}$$

Where A is the cross sectional area of the blade, E is the Young Modulus of Elasticity of the blade material.

The blade deflection, x_L as in Equation 3, of the structural material based on lift force, F_L is obtained from Equation 3

The blade deflection, x_C as in Equation 6, of the structural material based on centrifugal force, F_C is obtained from Equation 4 and F_C is the product of the mass of the blade, m and the acceleration due to gravity, g: $F_C = mg$, is numerically used to determine the inertia weight of the blade structural materials.

$$x_{C(0\to x)} = \frac{F_C}{AE}\int_0^L L dL \tag{6}$$

To validate the predicted result found based on the two blades (aluminium and beach wood), which were geometrically created using the same model dimensions and both blades, were experimentally subjected to the same loading conditions (found from the predicted result). The tests were carried out on a simple cantilever test rig and load to deflection were recorded for the comparative analysis

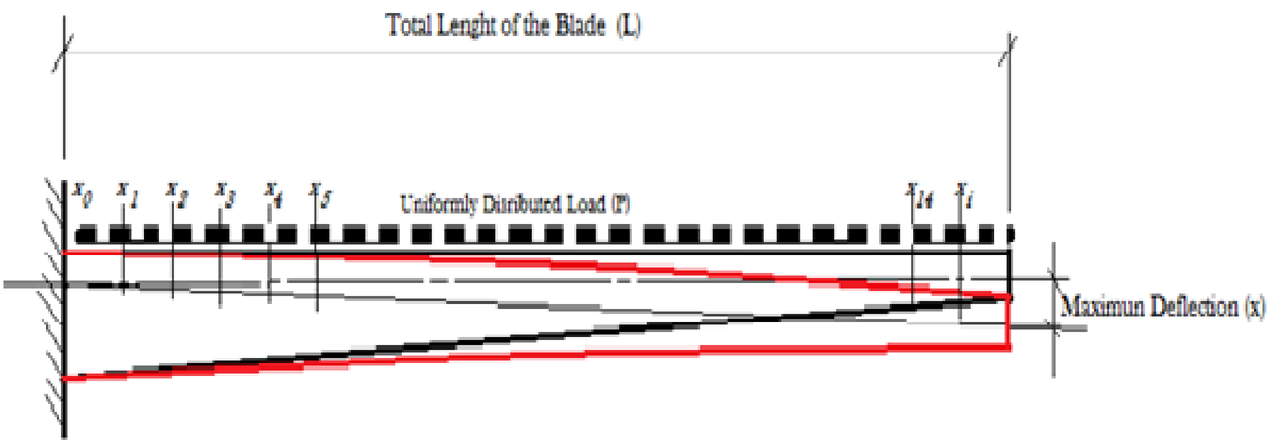


Figure 1. Schematic diagram of the blade as a cantilever with uniformly distributed load

Figure 2. Experimental test of the blade structural material under load deflection condition

2.3 Experimental Procedure

Based on the blade parameters and geometry developed by Ngala *et al*., (2016) and Shuwa *et al*., (2016), two blades were physically developed from the two selected blade structural materials; Aluminium and Beach wood. Each of the blades was hold by hydraulic pressure jack at the root on a simple cantilever test rig and loaded lap and edge wise. With a dial indicator, level plump and a parallel strip the deflection cause by the loadings were measured and recorded as in Figure 2.

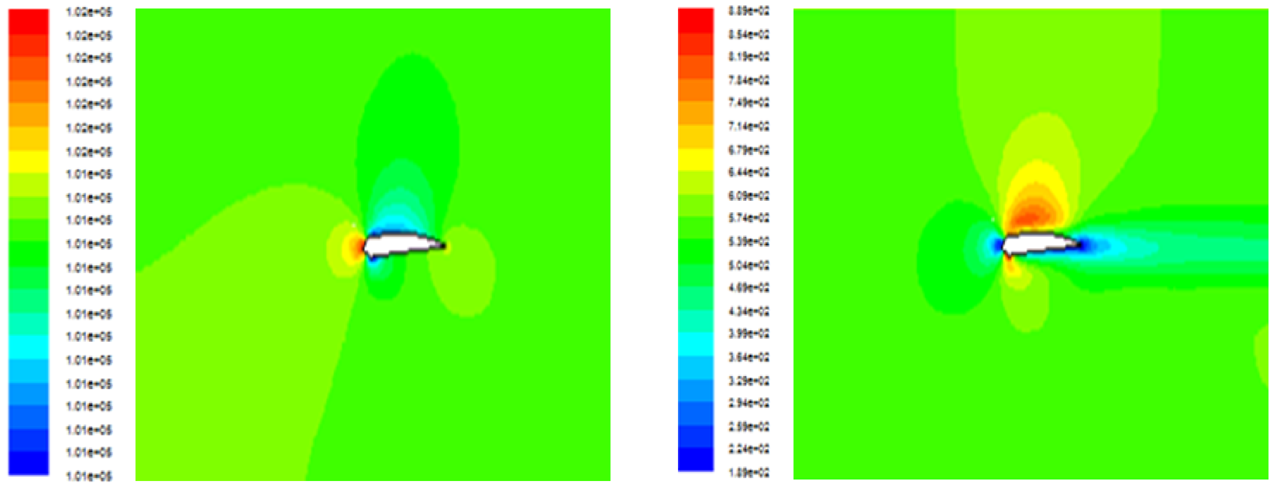
3. Result and Discussion

3.1 Influence of absolute and Dynamic Pressure on the Blade

The predicted results shown in Figure 3 (a and b) are for the contours of absolute pressure (a) and that for the dynamic pressure (b) over the blade sections and is for the aluminium material. The result in Figure 3a shows high pressure distribution of 1.02×10^5 Pa at the blade head and with slightly low wind pressure at the bottom. These are the causes of the edge-wise deflection of the blade structural material. Also shown in Figure 3b is the predicted dynamic pressure over the blade section, which reveals that the distribution of pressure amounts to about 8.89×10^2 Pa. This indicates that higher wind pressures are exerted over the lap-wise span of the blade.

3.2 Effects of Loading Deflection with Material Variation

Figure 4 and 5 shows the predicted behavior of the two blade structural material and in both cases, the loading deflection increases proportionally along the blade span from the root to the tip especially in under the lift force. Under the lift force, F_L of 236.285 N, the aluminium blade structure (Figure 4) shows a maximum blade tip deflection of 0.049 m (or 49 mm), while the beach wood (Figure 5) shows a maximum tip deflection of 0.098 m (or 98 mm).



(a) Absolute pressure (b) Dynamic pressure

Figure 3. Contours of Pressure on the wind turbine aluminium blade section

The deflections of the two blades structural material under lift and drag loadings were carried out experimentally. Figure 4 and 5 shows that when the blade is subjected flap - wise loading of 236.285 N at uniformly distributed lift force, F_L, the tip deflection of the aluminium blade structured material is 0.0500 m (or 50 mm) as in 4, while the beach wood blade shows a tip deflection of 0.0125 m (or 12.5 mm) as in 5. Under the edge - wise loading at uniformly distributed drag force F_D of 29.07 N, the aluminum blade shows a blade tip deflection of 0.0415 m (or 41.5 mm), while 0.0125 m (or 12 mm) is recorded on the beach wood blade.

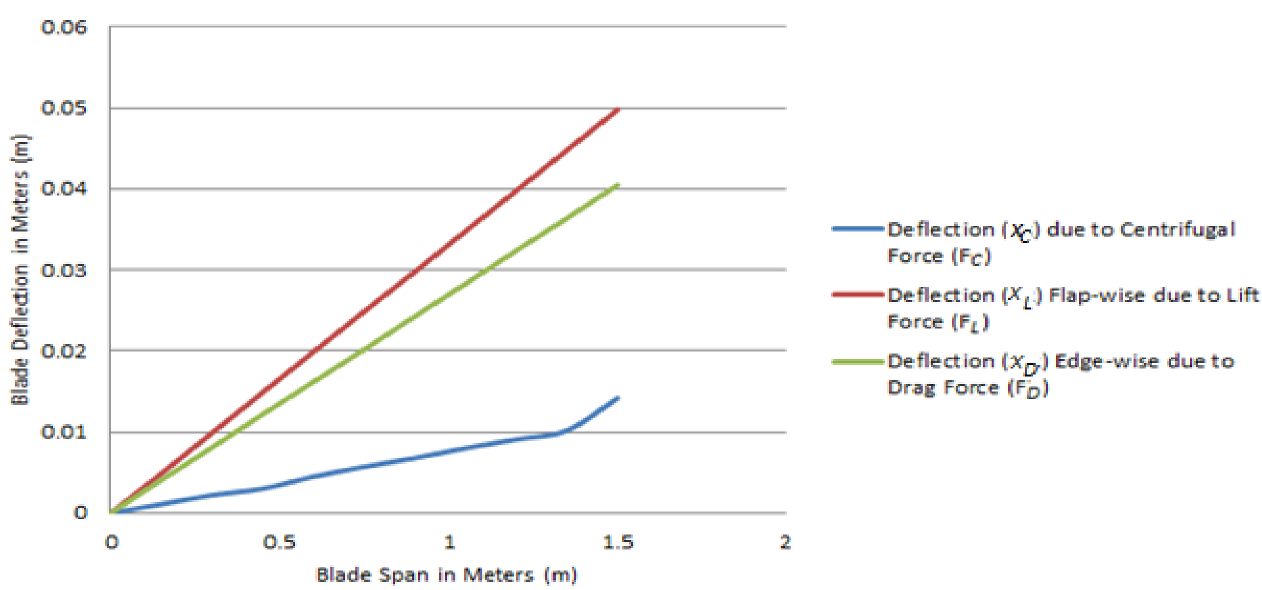


Figure 4. Predicted load deflection of the aluminium blade

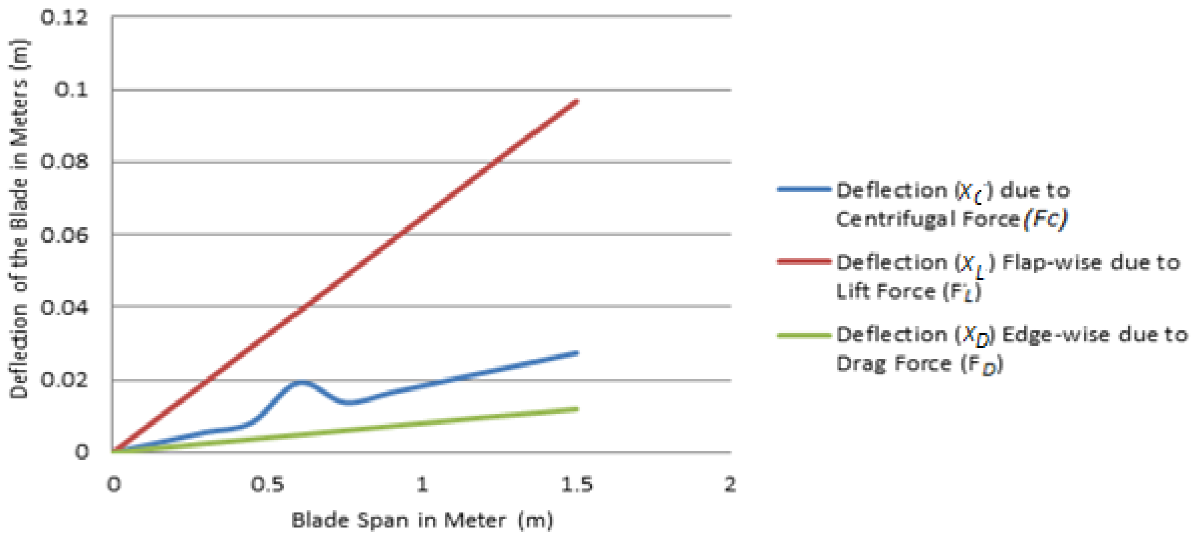


Figure 5. Predicted load deflection of the beach wood blade

Similarly from the experimental data shown in Figure 6, higher blade deflection were recorded as a result of lift force than the drag force for both structural materials, but the deflection in aluminium were lower than shown for the beach wood as in Figure 7. Figure 7 show that the blade structural material from beach wood has higher resistance to deflection under drag force than the aluminium blade structural material. In addition to the lift and drag related loads discussed above, even though the blade from this structural material have not experimentally subjected under centrifugal loadings. This was because the loads along the blade length have not been considered generally as design - controlling/life limiting loads. From the research work by Gujicic *et al*., (2010) for HAWT blade structure, they describe centrifugal loads as loads that do not control or limit blade design performance and has less or no impact on blade strenght design, hence in this reason it was therefore ignored at the experimental stage.

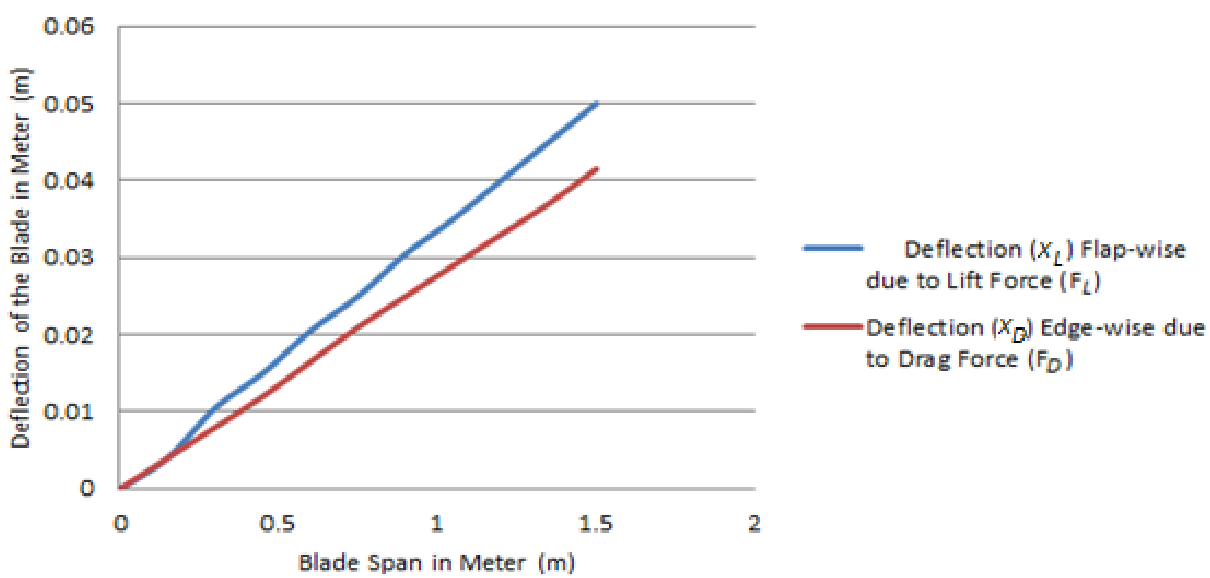


Figure 6. Measured load deflection of the aluminium blade span

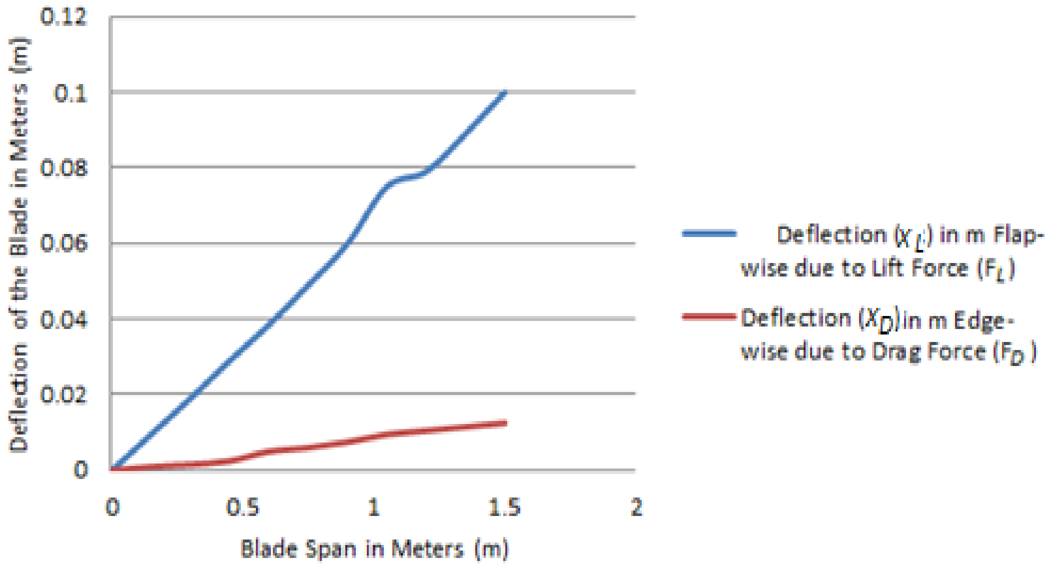


Figure 7. Measured load deflection of the beach wood blade span

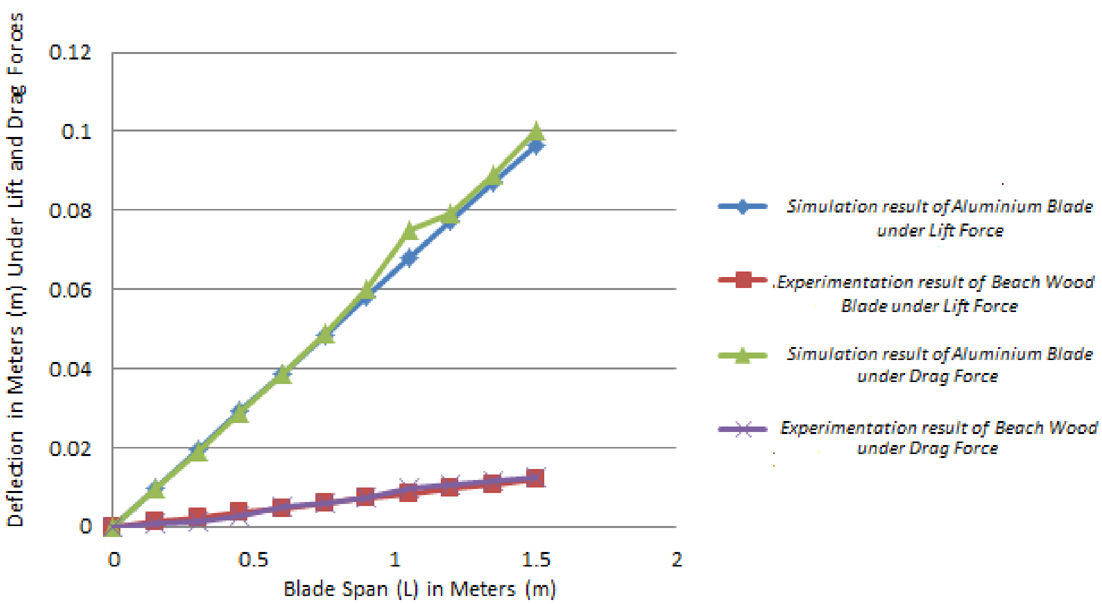


Figure 8. Comparison of predicted and measured blade deflection under Lift and drag forces

The flap - wise deflections of the blades is the major cause of blade failure in HAWT and excessive deflection will result in the blade, colliding with the tower causing total failure of the wind turbines. For this reason blade material with the list flap - wise deflection should always be the material with better preferance. However edge - wise deflection which have generally been shown to be the major causes of vibration, was also a factor in HAWT failure. Therefore, the blade from beach wood structural material gave better resistance to deflection under drag force than blade the aluminium structural material. But because instability in resistance was shown to be more pronounced in beach wood based on changes in weather conditions (Babu, 2006 and Chen *et al*., 2014), the use of it is unacceptable and aluminium is better selected for use.

3.3 Validation of the Predicted Results

Comparison of the predicted and measured deflection of the two structural materials was carried out, as shown in Figure 8. This was based on the statistical tool used: the T - test, which was for test in significant difference, Figure 8 shows that there is no significant difference between the prediction and experimental results, as the agreement between the two data is perfect for both the two structural materials. Figure 8 also reveals the accuracy of the comparative analysis, which indicates that the predicted deflections for other structural materials agrees could also be analysed. It also indicates that the CFD and the MATLAB tools could be used in analyzing the wind turbine materials prior to any experimentation.

4. Conclusions

Two horizontal axis blade materials were simulated base on the adopted geometry that was previously investigated, under an ultimate wind speed of 30 m/s. The said blades were physically developed from two locally available structural materials: aluminium and beach wood. These blades were tested and compared computationally and experimentally for the same aerodynamic loadings cause by lift and drag forces of 236.285 N and 29.09 N, respectively.

The computational result under these forces for the aluminium blade shows a maximum flap - wise deflection of 0.0498m and edge-wise deflection of 0.0405 m, while in the experiment the tip flap-wise deflection is 0.0500 m and the edge-wise deflection is 0.0401 m. The computational result of the beach wood blade shows a maximum flap - wise deflection of 0.0967 m and edge-wise deflection of 0.0119 m, while in experiment the flap-wise deflection is 0.1000 m and the edge-wise deflection is 0.0125 m. This shows that the aluminium blade has a better strength than the beach wood flap - wise, while edge - wise the beach wood has better resistance to deflection, but this may deteriorate because of the wood instability under wet environmental condition.

Also, the comparisons of the predicted lift and drag forces that the blades were subjected to and experimental results for both the aluminium and beach wood materials shows good agreement. This shows that the CFD tool used could be a reliable tool for the optimization of the wind turbine blade materials.

Furthermore, based on the data obtained for centrifugal force subjected to the blade as a result of its inertia force, the aluminium blade is lighter in weight than the beach wood blade built of the same geometry (CFD and experiment). Therefore the aluminium blade structural material is the most suitable under an ultimate wind speed of 30 m/s and for Maiduguri.

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