STM JOURNALS

Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 14, Issue 1, 2026
DOI (Journal): 10.37591/JoPC

https://journals.stmjournals.com/jopc

Research JoPC

Design And Analysis of Carbon Filler Reinforced Composite Small Wind Turbine Blades

Cheruku Srinivas Rao[1,*], B. Nageswara Rao[2], Subhash Kamal[3], Abrha Gebregergs Tesfay[4]

Abstract

Although wind turbines have great potential for capturing wind energy, their blades suffer from unstable aerodynamic loads as a result of operating for extended time in challenging conditions. Both structural and aerodynamic performance are negatively impacted by these loads. The effectiveness of the wind turbine and the use of wind energy are significantly impacted by the choice airfoil. Commonly used airfoils include NACA 4412, NACA 23012, and SG6043. The lift and drag characteristics of an airfoil blade or wing are primarily influenced by its geometric shape, along with the angle of attack. XFOIL program is used to compare the lift coefficient, drag coefficient and lift to drag ratio for NACA4412, NACA 23012 and SG6043 airfoils at Reynolds numbers 1.0 × 10 ^{5} and 5.0 × 10 ^{5}. Results like the drag, lift coefficients, lift to drag ratio vary with the Reynolds number and angle of attack which show that SG6043 airfoils have better average performance criteria with higher lift to drag ratio. A CAD model of the blade is designed using SolidWorks software and SG6043 airfoils. A polymer composite made of carbon filler epoxy and jute fiber wind turbine blade with a 1 MW power generating capability is designed and developed. The mechanical test revealed that the composite exhibits good tensile strength (average value of 932 MPa). The average strength of impact recorded for the composite was 152 kJ/m². Experimentally determined density was 1420 kg/m³ and shows that blades are light enough to be easily set in motion by the wind.

Keywords: Airfoil, angle of attack, composite blades, density, drag coefficient, impact, lift coefficient, tensile strength, Xfoil

INTRODUCTION

Global warming and the energy crisis have prompted a great deal of effort to learn more about renewable energy. Wind power is one type of renewable energy in which wind turbines capture wind energy and transform into fuel energy [1]. Consequently, the overall performance of the turbine can be enhanced by the ideal wind blade geometry [2]. The output metrics of the blade performance are reflected in the geometry of the blade, specifically distributions of airfoil types along the span, chord length and torsion angle distribution optimization and the ratio of blade thickness to chord length [3]. The selection of the airfoil, a component of the wind turbine blade, is also a crucial element that needs to be taken into account during blade design.

Natural fibers are biodegradable and have significant environmental advantages. Furthermore, compared to synthetic-fiber composites, they are typically easier to recycle, which aids in waste

***Author for Correspondence**
Cheruku Srinivas Rao
E-mail: srinivascheruku820@gmail.com

[1]Researcher, Department of Mechanical Engineering, KL University, Guntur, Andhra Pradesh, India.
[2]Professor, Department of Mechanical Engineering, KL University, Guntur, Andhra Pradesh, India.
[3]Dean and Faculty of Engineering and Technology, KBN University, Kalaburagi, Karnataka, India.
[4]Associate Professor, School of Mechanical and Industrial Engineering, Ethiopian Institute of Technology, Mekelle University, Mekelle, Ethiopia.

Received Date: November 21, 2025
Accepted Date: December 29, 2025
Published Date: January 05, 2026

Citation: Cheruku Srinivas Rao, B. Nageswara Rao, Subhash Kamal, Abrha Gebregergs Tesfay. Design And Analysis of Carbon Filler Reinforced Composite Small Wind Turbine Blades. Journal of Polymer & Composites. 2026; 14 (1): 79–89p.

reduction and the advancement of a circular economy in the wind energy sector [4]. In terms of economics, natural fiber composites are typically less expensive to manufacture than synthetic fiber composites [5].

The use of composite materials is common in wind turbine blade production due to their excellent mechanical properties and relatively lower weight compared with the use of steel or other metals [6]. Natural fibers are sometimes used as a substitute in some composite applications instead of carbon fibers. The advantages of natural fibers, as sisal, flax, hemp, jute, are the low costs, availability, and environmental friendliness. The disadvantages are the quality variations, high moisture uptake and low thermal stability of the raw fibers [7].

The performance of the blade is characterized by the lift and drag forces that result from the motion of an airfoil-shaped body in a fluid. By adjusting the airfoil's shape and angle of attack, the lift can be maximized [8]. A high lift-to-drag ratio is a general requirement for airfoil designs. Although it does not increase torque, raising the lift coefficient increases thrust, which lowers the drag coefficient and boosts aerodynamic efficiency [9]. Using analytical equations that describe the camber (curvature) of the mean-line (geometric center line) of the airfoil section as well as the thickness distribution of the section along its length, the early NACA airfoil series, the 4-digit, 5 digits and modified 4-/5-digit were created [10].

The airfoils chosen for this study are pertinent because the geometries are openly accessible and there is a wealth of experimental data that can be used to assess simulation results. The wind turbine database was used to choose various airfoil types recommended for small horizontal axis wind turbines. Current study compares NACA4412, NACA 23012 and SG6043 airfoils at Reynolds numbers 1.0×10^5 and 5.0×10^5 mainly using XFOIL program. For each airfoil, lift ratio, drag ratio, maximum lift to drag ratio and optimal attack angle were calculated and an experimental model of small wind turbine blades made of composite material was designed and developed.

METHODOLOGY

The enormous size of the wind turbine blades used to generate power, makes them labor-intensive and challenging to construct and test. The efficiency of the wind turbine depends on the airfoil selection, manufacturing difficulty, blade quality, and aerodynamic performance. In this case, the XFOIL software was used to compare and analyze the aerodynamic characteristics of NACA 4412, NACA 23012, SG6043 at Re 100,000 and 500,000 and AOA between −15 and 20 degrees. Of these, NACA4412 shows that the airfoil type has a maximum thickness of 12% at 30% chord and maximum camber of 4% at 40% chord length (Figure 1). NACA 23012 shows that the airfoil's maximum relative camber is 1.8%, in relation to the chord length 12.7% and maximum thickness of 10% (Figure 2). SG6043 has a maximum thickness of 10% at 32.1% chord and maximum camber of 5.1% at 53.3% chord length (Figure 3).

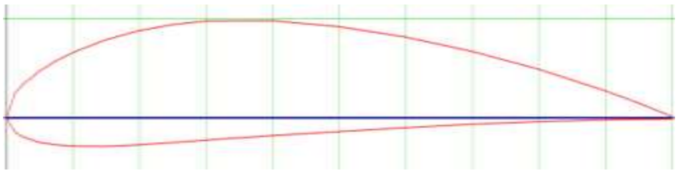

Figure 1. NACA 4412

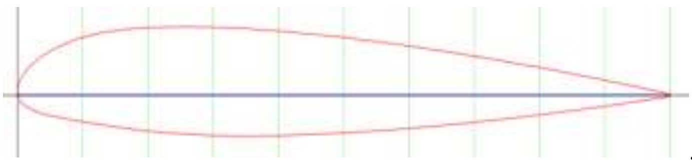

Figure 2. NACA 23012.

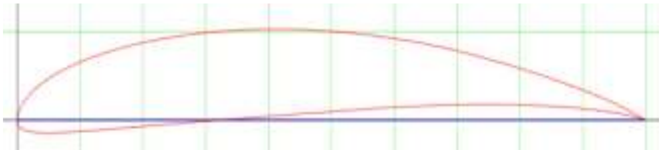

Figure 3. SG6043.

First digit indicates the maximum relative camber of the airfoil and the second digit indicates the position of the maximum relative camber relative to the chord length. The last three digits indicate the arc in the airfoil and its relative thickness [11].

The lift coefficient and drag coefficient are two crucial metrics that demonstrate the performance of the airfoil. Drag force is the parasitic force, while lift force generates the blade's rotational action. Although the parameters of two forces are the same, their coefficients differ. The following equation (1) is a representation of the blade's Reynolds number [12].

$Re = \rho vC/T$
ρ = Density of air (KG/m3),
v = Velocity of air (m/sec)
C = Chord length of blade (m)
T = Dynamic viscosity of air (N.Sec/m^2)

Glide ratio (GR), in addition to Re, is an important airfoil performance metric. Another name for it is the lift-to-drag ratio. Since it increases rotor torque and reduces bending moments on the rotor blade for a specific lift value, a higher lift to drag ratio is anticipated. Thus, the following equation (2) provides the glide ratio [13].

$GR=L/D=CL/CD$
L=Lift force(N)
D=Drag force (N)

A CAD model of the blade is designed using SolidWorks software and SG6043 airfoils. A polymer composite made of carbon filler epoxy and jute fiber wind turbine blade with a 1 MW power generating capability is designed and developed.

Composite preparation

The matrix was made by combining epoxy resin with Butanox M-60 hardener. A modified matrix is produced by adding carbon fillers at weight percentages of 10 [14]. To equally disperse the carbon fillers in the modified matrix, a mechanical stirrer operating at 200 rpm for 15 minutes was used to mix a predetermined quantity of fillers and resins in a container. The epoxy resin matrix was stirred for an additional two minutes after the appropriate quantity of hardener was added.

Manufacturing of composite blades

Aluminum molds, one for each type of blade with two separate components, were created in order to produce the wind turbine blades (Figure 4). The composite fibers were disposed of in the aluminum molds by switching between one layup of carbon fillers reinforced epoxy and one layup of jute fiber. Ultimately, jute fibers were positioned along the model to strengthen the airfoil. In the initial stage of manufacturing of blades degreasing of the mold is done with acetone followed by application of clearing agent to separate the structure after polymerization from the mold. Using a template similar to selected three airfoils, the composite fiber layups are cut. A wooden framework was positioned in the gripping zone where the blade and generator flange would be joined and one layup of carbon filled epoxy resin and one layup of jute fiber were placed on top of it (Figure 5). Applying a layer of peel ply is the last step to prevent the vacuum bag from sticking to the airfoil (Figure 6). The blades are cured at room temperature (23°C) for 24 h, followed by a post-curing stage at 60°C for 16 h to enhance mechanical properties and dimensional stability. The assembled composite small wind turbine blades and experimental model is depicted in Figure 7, Figure 8.

Figure 4. Alluminum molds for manufacturing the composite wind turbine blades.

Figure 5. Placement of epoxy resin and jute fiber layups.

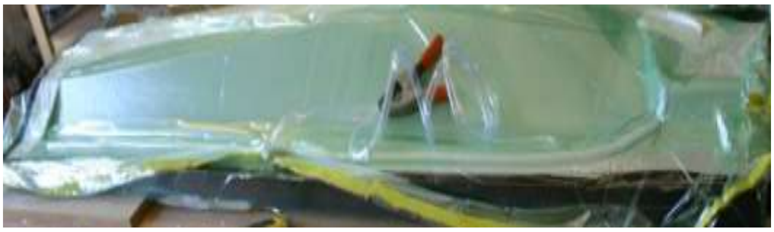

Figure 6. Mold under vaccum process.

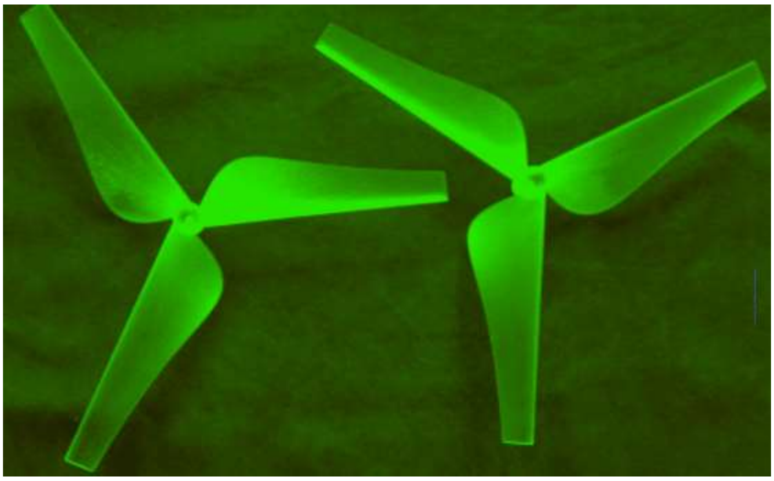

Figure 7. Experimental model made up of composite material.

Figure 8. Testing of experimental model.

Test for tensile strengths

Experiments were performed in compliance with ASTM D3039 guidelines with 100 kN load cell of MTS universal testing machine, at 1 mm/min cross speed under room temperature (Model 810 – Microcomputer Controlled Electro-hydraulic Servo Universal Testing Machine). Five specimens, each measuring 240 × 10 × 4 mm^3, were cut from composite.

Specimens immersed in water for 20 days were used in the test to determine the effect of water absorption and hybridization on the deterioration of the composite's tensile strength. Room temperature, 50°C, and 70°C were the three temperatures at which water was submerged.

Test for impact

ISO 179–1 (2010) guidelines was followed for conducting the Charpy impact test. Five unnotched specimens, each measuring 85 × 15 × 6 mm^3, were made for each test. Wet specimens were created by immersing in a water bath for 20 days in order to examine the impact of water absorption on the deterioration of the composite's impact strength. Pendulum Impact Testing Machine, Model: DI-Impact 300 with impact energy 300 J was used to perform the impact test. The specimens were pounded in both normal and flat direction. The experiments were conducted at room temperature.

Test for density

Density measurement was conducted using Archimedes' method and an analytical balance Pioneer PX224 (Ohaus) along with a density measurement kit for solids. The fluid employed for these measurements was ethanol (99.3% purity), which has a known density variation depending on temperature. An average value was calculated based on five separate measurements.

RESULTS

The X Foil software is used to analyse and compare NACA 4412, NACA 23012 and SG6043 airfoils at Re 1.0x10^5, and 5.0x10^5 and the angle of attack from -10 to 20 degrees. At Re 1.0x10^5, the highest lift coefficient of 1.63 for SG6043 at angle of attack 14.75° is observed followed by 1.44 for NACA 4412 and 1.03 is noted for NACA 23012 at the same angle of attack.

In contrast, the highest lift coefficient of 1.48 for NACA 4412 is recorded at an angle of attack of 14.25° and the highest of 1.27 for NACA 23012 is recorded at an angle of attack of 13° (Figure 8).

NACA 4412 has a drag coefficient of 0.028, NACA 23012 has a drag coefficient of 0.025, and SG6043 has the drag coefficient of 0.02 at angle of attack 6.75° at Re 1.0x10^5. On the other hand NACA 4412 registers the drag coefficient of 0.017 at an angle of attack of 1.5°, while NACA 23012 records the drag coefficient of 0.0147 at an angle of attack of 1°. SG 6043 thus had least drag coefficient at highest angle of attack compared to other two foils (Figure 9).

Results also show that for SG 6043 the average maximum lift to drag ratio at Re of 1.0x10^5 is 66.46 with an angle of attack of 7°, while for NACA 4412 airfoils it is 54.09. It is also observed that, lift to drag ratio for NACA23012 is 35.64 at same angle of attack. This indicates that SG 6043 airfoils are more effective in areas with low wind speeds. Conversely, the NACA 4412 had a lift to drag ratio of 56.1 at an angle of attack of 6.2°, while the NACA 23012 lift to drag ratio is 36.38 at an angle of attack of 5.5° (Figure 10).

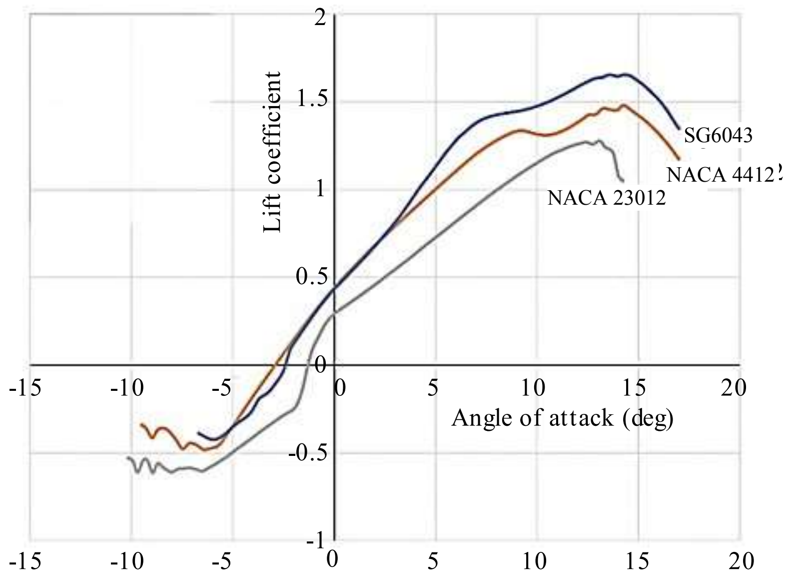

Figure 9. The lift coefficient performance curves for the NACA 4412, NACA 23012 and SG6043 airfoils at Re=1.0x10^5.

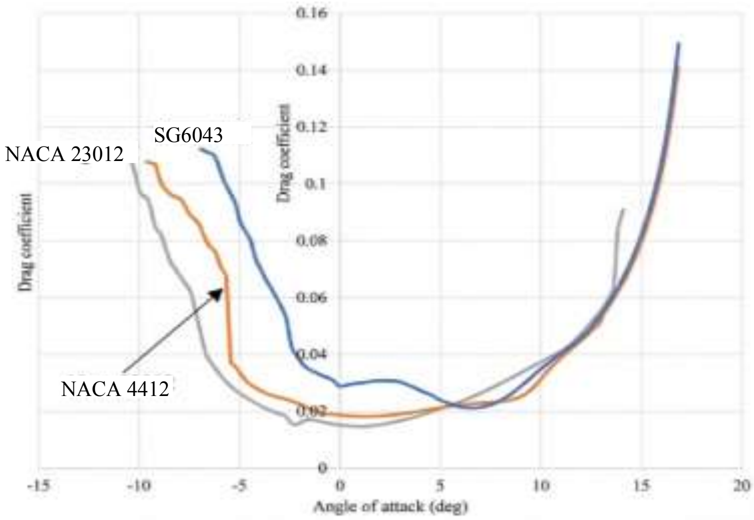

Figure 10. The drag coefficient performance curves for the NACA 4412, NACA 23012 and SG6043 airfoils at Re=1.0x10^5.

Journal of Polymer & Composites
Volume 14, Issue 1
ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

Figure 11 displays that, with an angle of attack of 15.5°, the highest lift coefficient of 1.7038 for SG6043, 1.517 for NACA 4412, and 1.40 for NACA 23012 at the same angle of attack are recorded at Re 5.0x10^5. While the highest lift coefficient of 1.43 for NACA 23012 is measured at an angle of attack of 14.25°.

At angle of attack 0.75° and Re 5.0x10^5, the drag coefficients of NACA 4412, NACA 23012 and SG6043 are 0.00693, 0.00723 and 0.00682 respectively. However, for NACA 4412 at angle of attack 0.25° the drag coefficient recorded was 0.05 (0.00681) whereas NACA 23012 has 0.05(0.00683) at angle of attack of 0.25° (Figure 12).

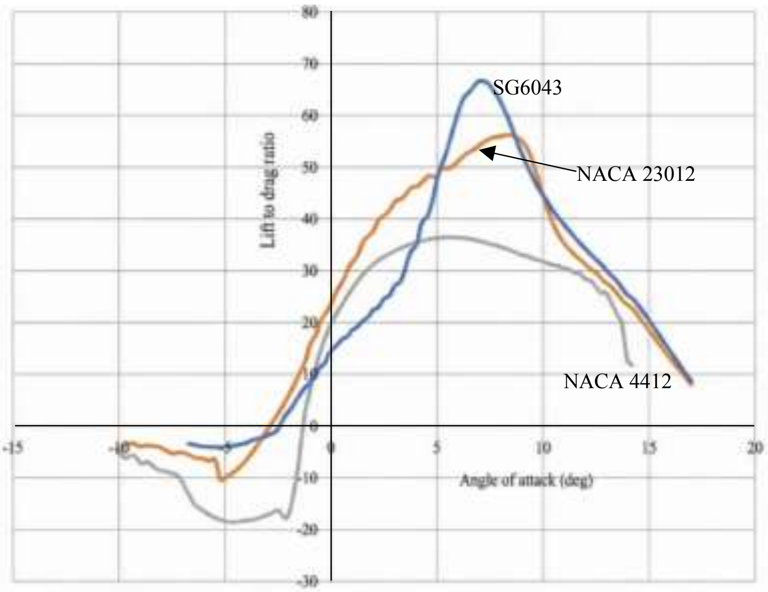

Figure 11. The lift to drag coefficient performance curves for the NACA 4412, NACA 23012 and SG6043 airfoils at Re=1.0x10^5.

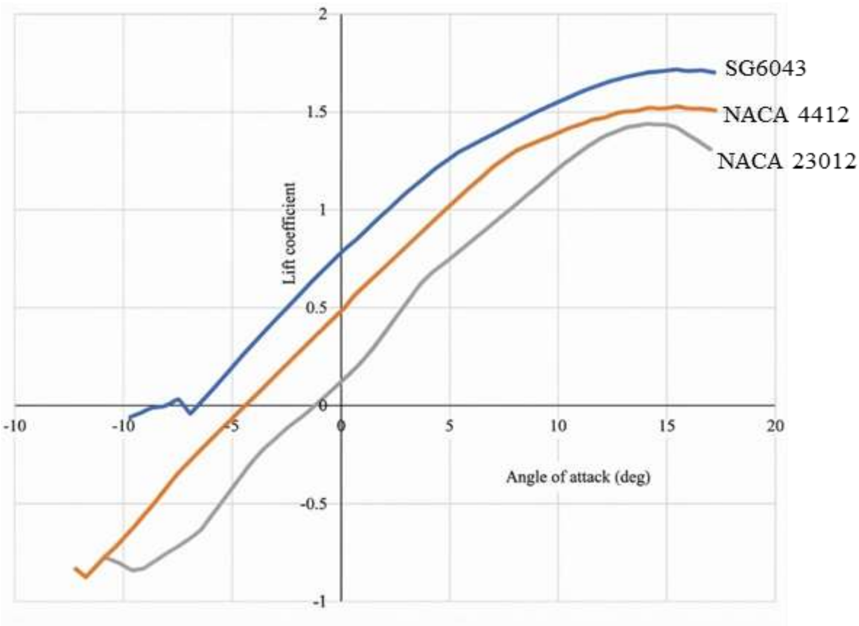

Figure 12. The lift coefficient performance curves for the NACA 4412, NACA 23012 and SG6043 airfoils at Re=5.0x10^5.

Figure 13 illustrates how the angle of attack affects the lift-to-drag coefficient ratio for the chosen airfoils at Re of 5.0x10^5. The highest ratio for SG 6043 reached at a 3.5 °angle of attack is 143, shows that lift is significantly higher than drag, which is ideal for small wind turbine design.

The higher lift to drag ratio value of this airfoil indicating that the theoretical aerodynamic performance of this airfoil is superior to the other two (Figure 14). The lift-to-drag ratio has an impact on the rotor torque and power generation, particularly at low wind speeds. Results also show that, the average maximum lift to drag ratio for NACA 4412 airfoils is 100.7 and for NACA 23012 is 60.3. Results also depicts that, the average maximum lift to drag ratio for NACA 4412 airfoils at angle of attack 6° is 108 and for NACA 23012 is 77 at an angle of attack of 9°.

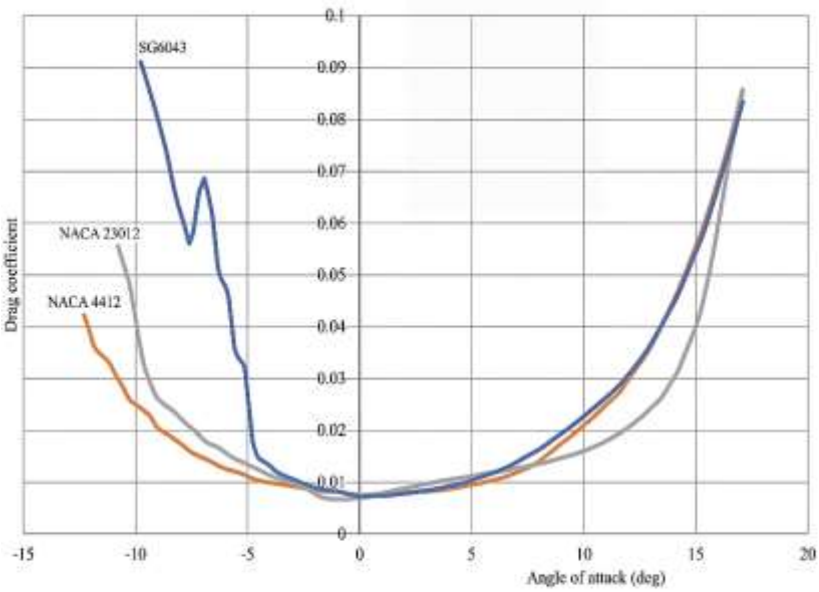

Figure 13. The drag coefficient performance curves for the NACA 4412, NACA 23012 and SG6043 airfoils at Re=5.0x10^5.

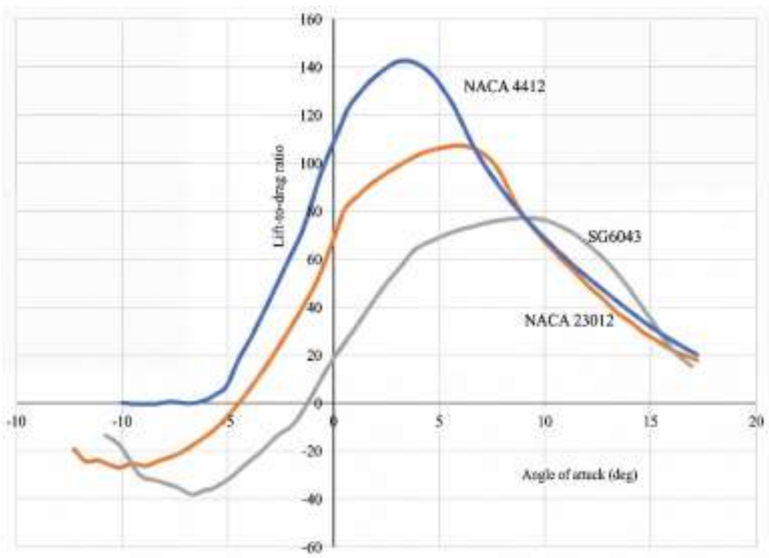

Figure 14. The lift to drag coefficient performance curves for the NACA 4412, NACA 23012 and SG6043 airfoils at Re=5.0x10^5.

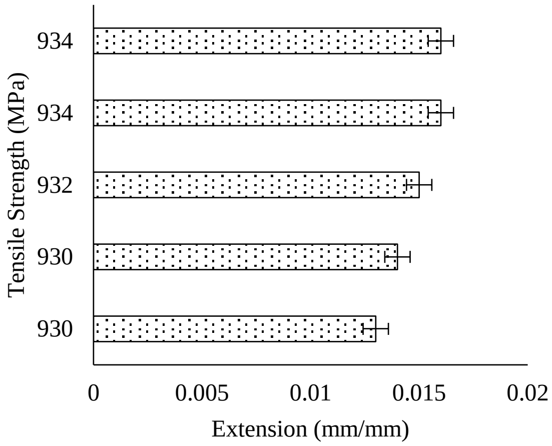

Figure 15. Mechanical test results depicting the average tensile strength of five samples with standard deviation

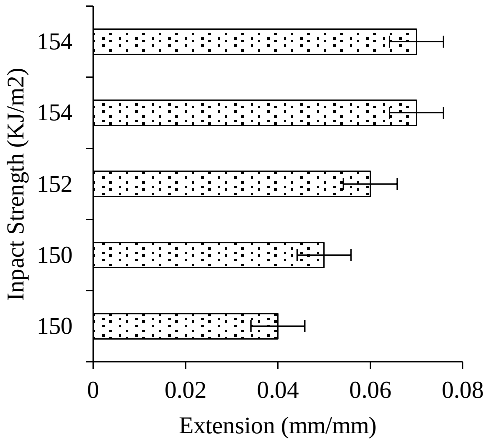

Figure 16. Mechanical test results depicting the average impact strength of five samples with standard deviation

The polymerization process at room temperature took place over a duration of 72 to 96 hours. Subsequently, the composite airfoils were removed from the molds, and additional post-processing methods were implemented to achieve the final experimental small wind turbine blade made of composite material is depicted in Figure 7, 8.

In order to ascertain the tensile characteristics of the chosen composite material used for small wind turbine blades, two different kinds of mechanical tests were carried out throughout this investigation. The mechanical test revealed that the composite \exhibits good tensile strength (average value of 932 MPa with a standard deviation of 0.0158) (Fig15). The average strength of impact recorded for the composite was 152 KJ/m^2 with a standard deviation of 0.068 (Fig16). Moreover, the experimentally determined density was 1420 kg/m^3 and it shows that the blades are light enough to be easily set in motion by the wind.

DISCUSSION

In wind turbine blade design, aerodynamic performance is crucial, and airfoil shape affects aerodynamics. It is crucial to make sure that the airfoil used to design wind turbine blades does not experience any operational instability. In particular, maintaining a relatively constant angle of attack is essential for pitch-controlled wind turbines in order to maintain full operability. The lift and drag coefficient describe the performance of airfoil. For all the selected airfoils of small horizontal wind turbine blades, as the angle of attack increases, the lift and drag coefficient increases till certain angle change. However, the rate of increment is much higher after a certain angle of attack due to flow separation [15]. Increase in the thickness, camber, and angle of attack of airfoil increases the lift coefficient [16]. Controlling flow separation on an airfoil improves the airfoil's performance by raising the lift coefficient, lowering the drag coefficient, and raising the lift to drag ratio [17]. The airfoil SG6043 has the highest lift coefficient and the flow separation occurs at the angle of attack 14.75°. Both the drag and lift coefficients account for the angle of attack (AoA). This angle of attack has a significant role in the magnitude of the lift and drag coefficient, which means that it also influences the amount of lift and drag force that is generated [18].

The operating Reynolds number of each airfoil is one of the key parameters. Reynolds number has a major impact on the airfoil's drag and lift characteristics and is a function of the airfoil's performance characteristics. As the Reynolds number decreases, the drag coefficient's overall level rises and additionally, the blade's Reynolds number tends to decrease as its length does [19]. There was an increase in the drag coefficient for SG6043, NACA 4412, and NACA 23012 as the Reynolds number decreased from 5.0×10^5 to 1.0×10^5. However, at both Reynolds numbers, the drag coefficient values with SG6043 were the lowest. An increase in Reynolds number results in an increase in the airfoils lift curve slope, maximum lift coefficient, and critical attack angle. Mueller and Batill on a range of airfoils also concluded that maximum lift coefficient consistently increases with higher Reynolds numbers and that the minimum drag coefficient significantly decreases [20]. For SG6043, NACA 4412, and NACA 23012, the lift coefficient increased as the Reynolds number increased from 1.0×10^5 to 5.0×10^5 with SG6043 recording the highest lift coefficient. Additionally, as the minimum drag coefficient falls, the lift to drag ratio increases [21].

Using a vacuum-assisted oven the same results can be obtained as in case of using the autoclave technology. Applying a layer of peel ply prevents the vacuum bag from sticking to the airfoil [22]. According to configurations evaluated by Bej et al[23]., the mechanical properties of the carbon fiber composite are better to those of the glass fiber composite. Similar to this carbon fillers used in the current investigation had shown high tensile and impact strengths for the composites.

CONCLUSION

Aerodynamic performance of the three different airfoils studied shows that SG6043 has the lowest drag coefficient value and highest lift coefficient at Reynolds number 1.0×10^5 and 5.0×10^5. SG6043 also depicted the highest lift to drag ratio at the same Reynolds number which increased with increase in Reynolds number and also increase in angle of attack. After a detailed aerodynamic comparison, it was concluded that SG6043 is the most suitable airfoil for the small horizontal axis wind turbine operating at low wind speeds. Hence SG6043 can be suggested as the best performing airfoil among the compared airfoils for the given Re range. Hence an experimental model of small wind turbine blades made of composite material was designed and developed using SolidWorks software and SG6043 airfoils and tested for tensile and impact strengths. In the present study, an experimental small wind turbine is assembled and tested in a wind tunnel to determine its performance.

REFERENCES

1. Mahmoud NH, El-Haroun AA, Wahba E, Nasef MH. An experimental study on improvement of Savonius rotor performance. Alexandria Eng J. 2012;51(1):19–25. doi:10.1016/j.aej.2012.07.003.
2. Hansen MOL. Aerodynamics of wind turbines: Rotors, loads and structures. London, UK: James & James (Science Publishers Ltd); 2000. [missing total pages] p.144.
3. Hu D, Li J. Numerical simulation of aerodynamic performance of wind turbine blade airfoil. Ren Ener Reso. 2011;29:134–142. [missing issue number] [missing DOI].

4. Xhao X, Copenhaver K, Wang L, Korey M, Gardner DJ, Li K, Lamm ME, Kishore V, Bhagia S, Tajvidi M, Tekinalp H, Oyedeji O, Wasti S, Webb E, Ragauskas AJ, Zhu H, Peter WH, Ozcan S. Recycling of natural fiber composites: Challenges and opportunities. Resour Conserv Recycl. 2022;177:105962. doi:10.1016/j.resconrec.2021.105962.
5. Ghalme S, Hayat M, Harne M. A comprehensive review of natural fibers: Bio-based constituents for advancing sustainable materials technology. J Ren Mat. 2025;13(2):273–295. doi:10.32604/jrm.2024.056275.
6. Kalkanis K, Psomopoulos CS, Kaminaris S, Ioannidis G, Pachos P. Wind turbine blade composite materials-End of life treatment methods. Energy Procedia. 2019;157:1136–1143. [missing DOI].
7. Vilar MMS, Khaneh Masjedi P, Hadjiloizi DA, Weaver PM. Analytical interlaminar stresses of composite laminated beams with orthotropic tapered layers. Compos Struct. 2023;319(1):117063. doi:10.1016/j.compstruct.2023.117063.
8. Burton T, Jenkins N, Sharpe D, Bossanyi E. Wind energy handbook. 2nd ed. Chichester, UK: John Wiley and Sons Ltd; 2011. [missing total pages] p.124.
9. Ahmed MR. Blade sections for wind turbine and tidal current turbine applications – current status and future challenges. Int J Ener Res. 2012;36(7):829–844. doi:10.1002/er.2912.
10. The NACA airfoil series. [Internet]. Retrieved from: https://web.stanford.edu [missing publication year] [missing access date].
11. Wang X. On wind generator blade design and 3D modeling. Thesis (Master of Engineering). North China Electric Power University; 2008. [missing place of university].
12. Gray A, Singh B, Singh S. Low wind speed airfoil design for horizontal axis wind turbine. Today Proc. 2012;45(2):3000–3004. [missing DOI].
13. Shah H, Bhattarai N, Lim CM, Mathew S. Low Reynolds number airfoil for small horizontal axis wind turbine blades. Sustainable Future Energy 2012 and 10th Forum: Innovations for Sustainable and Secure Energy; [missing dates]; Brunei Darussalam. [missing page numbers] [missing publisher].
14. Saiteja J, Jayakumar V, Bharathiraja G. Evaluation of mechanical properties of jute fiber/carbon nano tube filler reinforced hybrid polymer composite. Mater Today Proc. 2019;22(3):756–758. doi:10.1016/j.matpr.2019.10.110.
15. Dhakal S, Bhattarai KR, Sanjay M. Computational analysis of the aerodynamic performance of NACA 4412 and NACA 23012 airfoils. Int Res J Eng Tech. 2023;10(12):265–275. doi:10.13140/RG.2.2.31495.37284.
16. Rad M, Kazemi FJ. Effect of camber and thickness on the aerodynamic properties of an airfoil in ground proximity. Int J Eng. 2001;14(3):273–280. [missing DOI].
17. Yousefi K, Saleh R, Zahedi P. Numerical study of flow separation control by tangential and perpendicular blowing on the NACA 0012 airfoil. Int J Eng. 2013;7(1):10–24. [missing DOI].
18. Winslow J, Otsuka H, Govindarajan B, Chopra I. Basic understanding of airfoil characteristics at low Reynolds numbers (10^4–10^5). J Aircraft. 2018;55(3):1050–1061. doi:10.2514/1.C034415.
19. Fuglsang P, Bak C. Development of the Risø wind turbine airfoils. Wind Ener. 2004;7:145–162. doi:10.1002/we.117.
20. Mueller TJ, Batill SM. Experimental studies of separation on a two-dimensional airfoil at low Reynolds numbers. AIAA J. 1982;20(4):457–463. doi:10.2514/3.51095.
21. Martínez-Aranda S, García-González AL, Parras L, Velázquez-Navarro JF, del Pino C. Comparison of the aerodynamic characteristics of the NACA0012 airfoil at low-to-moderate Reynolds numbers for any aspect ratio. Int J Aerospace Sci. 2016;4(1):1–8. doi:10.5923/j.aerospace.20160401.01.
22. Vintila IS, Condruz MR, Fuiorea I, Malael I, Sima M. Composite wind turbine blade using prepreg technology. 6th CEAS Air & Space Conference Proceedings; 2017; pp.5–14. [missing place of conference] [missing publisher].
23. Bej A, Borideasu I, Milos T, Badarau R. Consideration concerning the mechanical strength of wind turbine blades made of fiberglass reinforced polyester. Mater Plast. 2012;49(3):212–218. [missing DOI].

