Fabrication of Small-Scale Wind Turbine Composite Blades by the Hand Lay-Up Technique: An Industrial Approach

N. Yashas Singh[1], H.T. Chirag[1], N.B. Pradeep[1], H.S. Chandana[1], V. Prema[1], A.R. Anil Chandra[2,*], B.G. Suhas[2] and T.S. Srivatsan[3]

[1]Department of Electrical & Electronic Engineering, B.M.S. College of Engineering, Bangalore 560 019, India

[2]Department of Mechanical Engineering, B.M.S. College of Engineering, Bangalore 560 019, India

[3]Department of Mechanical Engineering, The University of Akron, Akron, Ohio, USA

Abstract: In harnessing wind energy, turbine blades play a crucial role due to which their design and manufacturing is given paramount importance. Various fabrication techniques, such as hand lay-up, vacuum bagging, and resin transfer moulding (RTM), for fabrication of the blade with the focus being on minimizing cost and defects while at the same time achieving precision in both geometry and dimension. This study focuses on fabrication of 1 m long turbine blade with helix angle, using the conventional hand lay-up technique. Carbon fiber and Epoxy resin were used primarily because of their high strength-to-weight ratio and durability. The fabrication process included the following: (i) mould design, (ii) sequential carbon fiber lay-up, (iii) resin application, (iv) curing, and (v) finishing. Key parameters, such as (i) fiber orientation, (ii) resin content, and (iii) curing time, were optimized for the purpose of obtaining quality product. Subsequently, the resulting blades were evaluated for dimensional accuracy, and blade density. This study highlights the nuances in fabrication of small-scale wind turbine blades using the hand lay-up technique as it is an effective method due to its low cost, flexibility in design, and suitability for complex shapes, thereby making it an ideal choice for customized blade production. Furthermore, this method ensures affordability for large scale applications as well as fabrication in small batches.

Keywords: Small-scale wind turbine blades, Hand lay-up fabrication, Carbon fiber–epoxy composites, Composite blade manufacturing, Prototype.

1. INTRODUCTION

Wind energy is one of the fastest growing renewable and environmentally friendly energy sources in the prevailing and ongoing era [1]. As countries and industries tend to focus more on reducing pollution and gradually moving toward sustainable power, wind energy has grown in strength to become a key technology in the energy sector. The wind turbine itself is a complex system, and among its various parts, the blades play a crucial role [2]. Therefore, it is both essential and desirable that the blades must have high specific stiffness and high specific strength to withstand intense winds and continuous rotation [3, 4]. Besides mechanical strength, blades must resist fatigue the resultant weakening that occurs due to repeated stress over time and the dire need to avoid failures. Moreover, since blades are often exposed to weather elements, good resistance to environment-induced degradation or corrosion is both essential and desired to ensure long life and reliable operation [5, 6]. Due to these requirements, reinforced composite materials have become the material of choice for large-scale wind turbine blades. The trend in wind turbines is gradually moving toward bigger and more powerful units. This necessitates that the blades are designed to be lightweight to reduce the load on the turbine while concurrently improving performance. These materials combine fibers like glass or carbon with resin to create a lightweight and strong structure [7]. Large wind turbine blades are made from fiber reinforced composites using thermosetting base resins. The blades are produced through a lay-up process [8, 9]. The superior strength-to-weight ratio [σ/ρ] of composite materials significantly improves overall efficiency of the wind turbine blades, particularly under low wind conditions. This feature enables turbines to sustain energy production across a range of wind speeds, thereby ensuring a seamless transition between low wing period and high wind period. Consequently, the system has the capability to deliver more stable and reliable power output in variable wind environments [10].

Various fabrication techniques, such as hand lay-up, vacuum bagging, and resin transfer moulding, have been used to manufacture composite structures, and thereby offer advantages in strength, precision, and weight reduction. One of the most widely used manufacturing methods for wind turbine blades, especially in small size to medium size, is the hand lay-up technique. This is a manual, hands-on process that involves the following: (i) placing layers of fiber reinforcement on a mould, (ii) coating these layers with resin, and (iii) then allowing the composite to cure and harden [11, 12]. The hand lay-up is popular primarily

*Address correspondence to this author at the Department of Mechanical Engineering, B.M.S. College of Engineering, Bangalore 560 019, India;
E-mail: aranilchandra@gmail.com

Received on 06-08-2026 Accepted on 15-09-2026 Published on 21-09-2026

E-ISSN: 2409-9848/26

because it requires low capital investment when compared to other manufacturing methods. Further, it is also flexible thereby allowing for different fiber orientations and materials to meet design requirements without the need for expensive tooling [13]. The manufacturing process commences with mould preparation made up of Medium Density Fiber board (MDF). The mould is then cleaned thoroughly to remove dust or grease. A release agent is applied so that after curing, the blade can be easily separated from the mould without experiencing any damage [14, 15]. This is followed by manually placing dry fiber mats, like glass fiber or carbon fiber, onto the mould surface. The fiber layers are arranged carefully in specific orientations to maximize mechanical properties, such as (i) tensile strength, and (ii) stiffness, since these properties depend heavily on fiber direction [16, 17]. Application of the resin is made using brushes or rollers. Epoxy resin is the most common choice because it bonds well with fibers and cures into a strong, durable matrix [18]. Complete wet-out is essential at this stage as the resin must fully impregnate all fiber layers, thereby ensuring a strong fiber-to-resin bonding while concurrently preventing weak spots: and compaction is done manually using hand rollers. Subsequently, the blade is allowed to cure. The curing process can take place at room temperature [27 °C], or in an oven depending on the resin system. Few manufacturers tend to use vacuum bagging during curing, which applies uniform pressure, removes excess resin, and does improve overall quality of the laminate by minimizing the number of voids [19]. The blade is carefully removed from the mould after the curing process. The finishing steps involve the following: (i) trimming excess material, (ii) sanding surfaces for smoothness, and (iii) applying coatings to protect against ultraviolet [UV] rays, moisture, and mechanical damage. The pressure of air pockets or uneven resin distribution can create defects that reduce mechanical strength or cause the early occurrence of failure [20, 21]. The HLP method does help in removing trapped air bubbles while distributing the resin uniformly.

Despite its several advantages, hand lay-up has few limitations. It is labour intensive, requiring the need for skilled operators, which makes the process time-consuming and concurrently increases labour costs [12]. Since the method depends heavily on manual work, productivity is limited, and scaling up production for large volume manufacturing is often difficult [13]. Additionally, the thermosetting resins often release volatile organic compounds (VOCs) during fabrication. This does pose as a health risk to workers and presents environmental concerns [11]. Considering the challenges identified in the conventional hand lay-up process, this research study focuses on the fabrication of small-scale wind turbine blades for low velocity wind turbine system. The objective of this study is to fabricate a composite wind turbine blade with a helical/twist angle using a reliable manufacturing method, which is suitable for small wind turbine system. The choice of a 1.1 m blade length is specifically dictated by the target operational domain of Small Horizontal Axis Wind Turbines (SHAWTs) designed for residential or decentralized micro-generation in low wind velocity regimes (≤ 5 m/s). A 1.1 m radius yields a rotor diameter of 2.2 m, which fits the standard geometric footprint of micro-turbines. Furthermore, this scale allows for direct experimental validation in standard subsonic wind tunnels and field testing setups without introducing scaling distortions or aerodynamic scaling conflicts. Lastly, this length directly builds upon the optimized aerodynamic geometric envelope established in Part I of our earlier research track [22]. This study did focus on the use of carbon fiber-reinforced composites, mould cutting and vacuum-assisted curing for the purpose of fabrication of the blades. For a low-velocity wind turbine, the primary bottleneck is overcoming the static drivetrain friction and rotational inertia to achieve a low cut-in wind speed. Carbon fiber provides an exceptional strength-to-weight ratio, yielding an ultra-lightweight blade shell. This drastically lowers the mass moment of inertia, enabling the blade to self-start under gentle wind streams where a heavier glass-fiber blade would remain stationary. Further, the superior tensile modulus of carbon fiber locks the precise 3D twist distribution in place under load. Hence carbon fiber/epoxy composite is the material of interest. Moreover, by utilizing hand layup technique with vacuum bagging we would like to demonstrate that high-performance materials can be processed successfully into complex, highly twisted aerodynamics without requiring expensive autoclave infrastructure. This offers a highly viable paradigm for high-efficiency, localized production without massive tooling investments.

2. METHODOLOGY

2.1. Materials and Methods

A schematic representation of the process followed for the fabrication of the wind turbine blade using woven carbon fiber cloth by hand lay-up technique is shown in Figure **1**.

2.2. Preparation of Mould

The initial step to fabrication of the wind turbine blades was to fabricate the mould as shown in Figure **2**. The wind turbine blade mould does involve a structured workflow that integrates digital modelling with CNC-based manufacturing. The process begins with

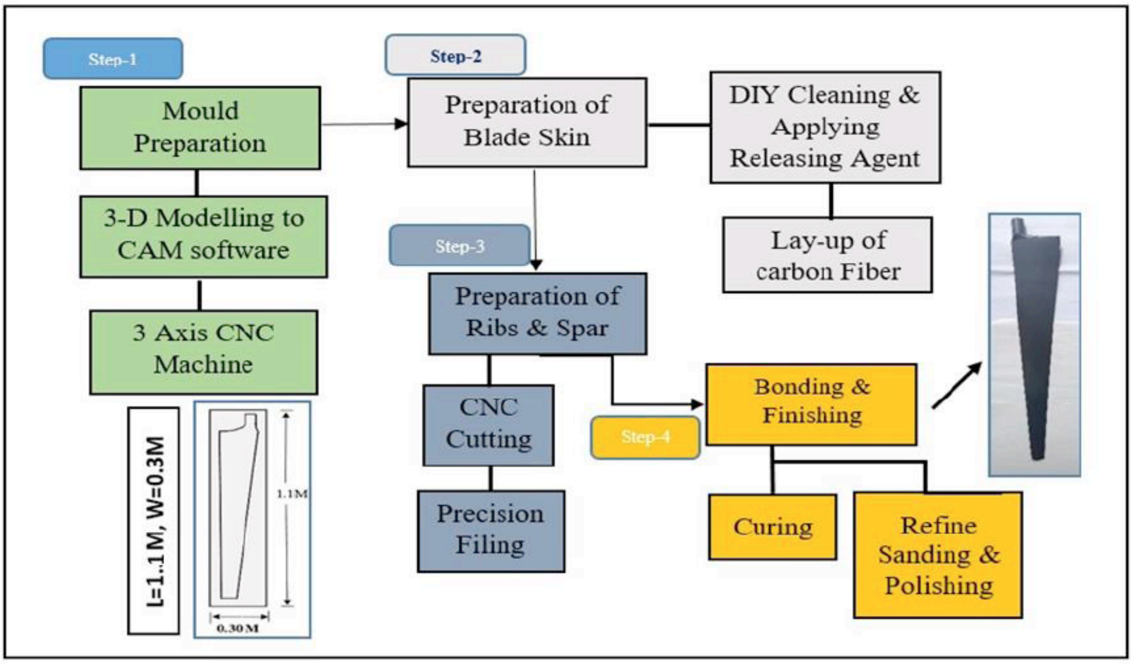

Figure 1: Process conducted to fabricate the wind turbine blades at present work. The reason for selecting the blade dimension is discussed in [22].

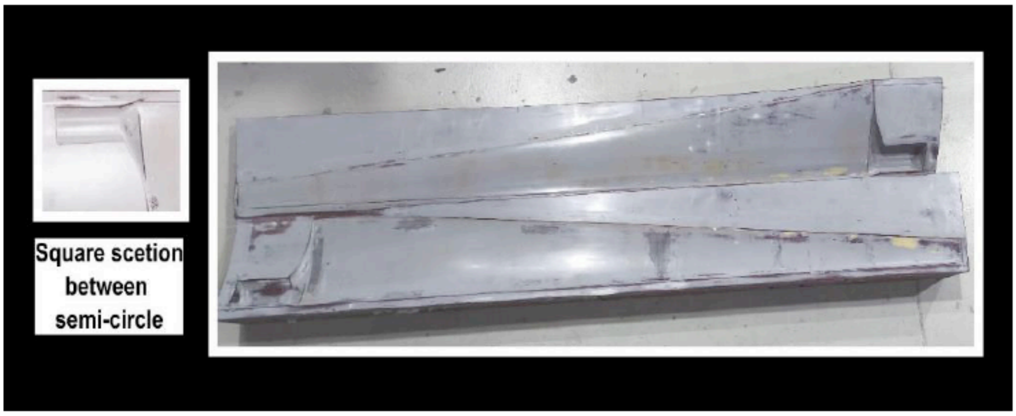

Figure 2: Medium density fiber board mould.

the aerodynamic design of the blade profile using Computer-Aided Design (CAD) software, thereby enabling, and ensuring both geometric accuracy and dimensional precision. After finalization of the design, it is exported in a compatible format and imported into the Computer-Aided Manufacturing (CAM) software for the purpose of generating toolpaths suitable for CNC machining. These toolpaths help in guiding a 3-axis CNC milling machine to shape the mould from a medium-density fiber board (MDF), the material chosen due on account of its smooth surface, uniform texture, and excellent machinability. After milling, the MDF surface is carefully sanded using 120-grit to 150-grit sandpaper for the purpose of removing tool marks and thereby help in achieving a clean and uniform finish. This surface preparation step is essential to ensure high-quality surface replication in the composite blade during the moulding process. This is essential as it promotes proper adhesion between layers while concurrently minimizing surface defects or irregularities.

2.3. Fabrication of Blade Skin

The mould is thoroughly cleaned using water to remove any dust or contaminants. This is followed by a layer of KAPCI® coating that is applied to cover any surface cracks and marks on the mould, as shown in Figure **3.1**. Photovoltaic (PV) liquid is applied on the mould surface to ensure easy removal of the blade skin after curing and it requires 2-3 hours to dry. Followed by Gel coat, a mixture of resin filler and resin hardener is prepared in a ratio of 1:3 and applied on the mould. This is shown in Figure **3.2**. Four layers of 160 GSM carbon fiber are wetted by the Resin and carefully laid on the MDF mould. Extra two layers of 160 GSM carbon fiber are laid on the tip of blades to ensure overall structural straightness. This is shown in Figure

Figure 3: Steps followed in the hand layup technique of fabricating medium density fiber board.

3.3. A single layer of peel ply, measuring 1600 mm in length, 400 mm in width, and 0.2 mm in thickness, was then placed over the layup. This was followed by a breather layer, having dimensions of 1700 mm × 500 mm and a thickness of 1 mm, which is placed over the lay up to aid in the curing process as shown in Figure **3.4** and Figure **3.5**. The breather layer is removed once the blade skin is dry.

Finally, the mould was sealed using a vacuum bag to ensure proper bonding and shape as is shown in Figure **3.6**. After 6-8 hours, the vacuum is released, and the cured blade skin is then carefully removed from the mould.

2.4. Support Structure for Blade

Following fabrication of the blade skin, the internal structural components, to include the ribs and spar, are then prepared to provide the necessary reinforcement. These components are constructed by sandwiching 4 mm wood with 160 GSM carbon fiber. Purpose of the fiber is to make possible an optimal balance of strength while concurrently enabling minimal weight. They are initially cut using a CNC machine and subsequently refined manually through filing to ensure a precise match with the blade's internal shape.

The spar provides longitudinal support and helps in maintaining the blade's structural alignment, while the ribs preserve the cross-sectional shape of the blade, to ensure in (i) dimensional accuracy, (ii) efficient load distribution, and (iii) an increase in mechanical strength. Once prepared, these components are carefully positioned and secured onto the blade skin for the purpose of enhancing overall structural integrity and performance as is shown in Figure **4**.

2.5. Bonding of the Blade

Prior to initiating the bonding process, it is essential to prepare both the blade mould and the necessary

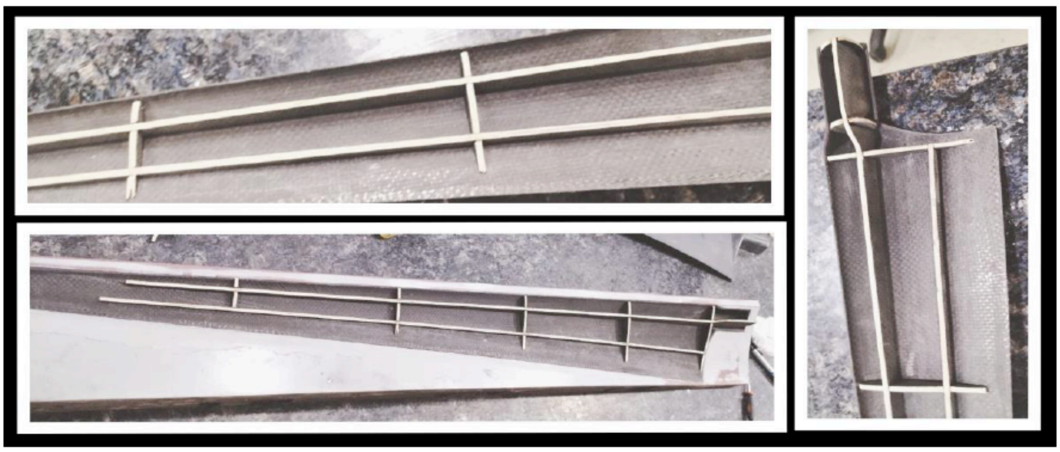

Figure 4: The Ribs and Spar placed inside the blade skin.

Figure 5: Structure adhesive applied on ribs and spar.

adhesive. An adhesive mixture was prepared using a ratio of sixty grams to thirty grams, and a thick gel coat was formulated for the purpose of bonding. The blade mould is thoroughly cleaned and waxed to ensure that the blade skin does not stick to the mould surface.

Once cleaned, the blade skin was positioned and held in place using tape. The next step involves arranging the support structure, which includes the ribs and spar, onto the blade skin and is shown in Figure **4**. The prepared adhesive was applied to both the ribs and spar to ensure proper fitment, and additional adhesive was also applied to the blade skin to ensure secure bonding. This is shown in Figure **5**. Finally, both halves of the mould are combined for bonding and left to set for 6-8 hours, to allow for proper bonding and curing.

The structural reinforcement consisted of a 160 GSM carbon fiber cloth, which was impregnated with an Araldite LY556 epoxy resin matrix blended stoichiometrically with an amine-based hardener. Layup was executed in a climate-controlled environment maintained at ~25°C (RT) and a controlled relative humidity of 50% to mitigate moisture contamination and prevent amine blushing. Following ply stacking, the assembly was vacuum-sealed and subjected to a 30-minute debulking phase under an absolute vacuum pressure of ~0.9 bar to extract trapped interlaminar air. This pressure was maintained throughout the primary green curing stage at room temperature (RT. To complete cross-linking, the cured composite underwent a thermal post-curing cycle inside a convection oven. The temperature was ramped to average temperature of 80°C for 2 hours, followed by an elevation to 100°C for 4 hours, before concluding with a controlled cooling rate to eliminate residual thermal stresses across the twisted blade profile.

2.6. Finishing of Blades

Following the bonding process, the next step involved finishing. In the finishing process the excess edges of the blades are carefully trimmed to remove all surplus material. The edges were then sanded

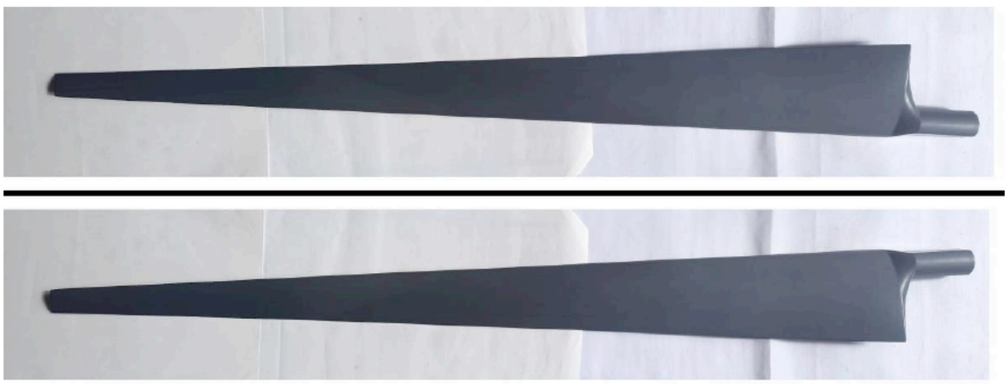

Figure 6: Fabricated Wind Turbine Blades.

precisely using P80 grit, P220 grit, and P400 grit sandpaper to help in achieving a smooth surface.

Following dry sanding, the blades undergo water sanding to further refine the finish and to remove any remaining imperfections. Once the process of water sanding was completed, a rubbing compound was applied to the blade surface to enhance the final finish and concurrently give the blades a polished appearance. This polished surface reduces friction and does help in the following: (i) maximize airflow over the blade, (ii) improving its aerodynamic performance, and (iii) efficiency.

3. CHALLENGES FACED AND CHALLENGES OVERCOME

3.1. Challenges Faced

- Helically curved blade surface and cutting of the mould presented difficulty in achieving a precise round shape for the blade handle. More on the necessity of maintaining the helical twist is discussed in [22, 23].
- Maintaining balanced blade weight was critical since any imbalance can adversely affect performance and stability.
- Colour matching of the blade skin posed aesthetic challenges, necessitating the need for consistency in tone across multiple blades.
- Accurate mixing of structural adhesive was essential; incorrect proportions led to poor bonding between the blade skin and internal structure, which eventually results in blade failure.
- Shaping the spars and ribs proved to be a challenge since the inaccuracies compromise the structural integrity.
- Mixing of the resin coat in the correct ratio was crucial to ensure proper curing and surface finish.
- Managing and working with carbon fiber might introduce potential health concerns. This is because fine fibers and dust particles do pose respiratory and skin-related risks and hence proper safety measures are to be followed.

3.2. Overcoming Challenges

- Achieve the desired round shape for the blade handle, the mould was designed with semi-circular ends and a square section in between. This is shown in Figure **2**, allowing for a more accurate and consistent curvature.
- Blade weight was maintained well within a tolerance of ±5% to ensure balance and optimal performance.
- Colour matching of the blade skins was achieved by using identical pigment formulation and application method as is shown in Figure **3.2**. This did enable in ensuring visual consistency across all blades.
- The structural adhesive was mixed in a precise ratio of 1:2 to ensure strong bonding between the blade skin and internal components.
- Spars and ribs were shaped with high accuracy to eliminate any visible gaps after bonding as shown in Figure **4**. This did help in enhancing structural integrity.
- The resin coat was prepared in a consistent ratio of 1:3 to ensure proper curing and enhanced finish quality.
- Appropriate personal protective equipment (PPE), including masks, gloves, and goggles, was used during handling of the carbon fiber materials. This was primarily because of the intent to mitigate potential health risks associated with fine fiber particles.

4. RESULTS AND DISCUSSIONS

4.1. Blade Density 380 g

The carbon fiber wind turbine blade fabricated was characterized to determine its mass-to-volume ratio and the resulting blade density**.**

The fabricated carbon fiber wind turbine blade was measured, and its mass was recorded to be approximately 380 grams. The volume of the blade was determined using the dimensional data extracted from the blade's design drawing in Solid Works and did provide a calculated volume of 682,981.28 mm³. This is shown in Figure **7**. The blade density was calculated using the expression or relation:

$$\rho = \frac{\text{mass}}{\text{volume}}\ g/cm^3$$

$$\rho\ = \frac{380\ g}{682.98\ cm^3}\ = 0.556\ g/cm^3$$

The calculated density of the blade is approximately 556 kg/m³, which indicates a lightweight structure optimized for the purpose of wind turbine applications. The low density is primarily due to its internal support structure, which comprises of ribs and a spar that significantly reduce the overall mass of the blade. This design not only just reduces the blade's weight but also enhances its aerodynamic efficiency while concurrently

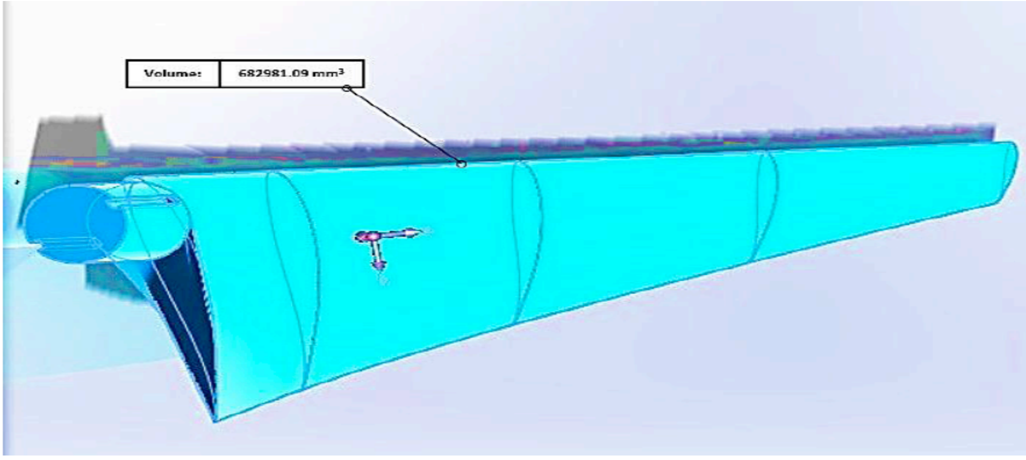

Figure 7: Volume of the blade in Solid Works.

enabling in rotation under conditions of low wind speed. This makes it well suited for wind turbine applications.

4.2. Dimensional Accuracy

The dimensional accuracy of the fabricated carbon fiber wind turbine blade was evaluated by comparing the measured dimensions to the SolidWorks® design specifications. The blade was designed for a total length of 1.1 meters and is shown in Figure **8(A)**. This includes a 70 mm arm with a radius of 20 mm for hub insertion and is shown in Figure **8(D)**. The blade's chord width tapered from 266.91 mm at the root to 64.88 mm at the tip. This is shown in Figure **8(B)** and Figure **8(C)**.

The fabricated blade was measured to have the following dimensions: (i) total length 1070 mm, (ii) arm length 70 mm, (iii) arm radius 20 mm, (iv) chord width at root 260 mm, and (v) chord width at tip 63 mm.

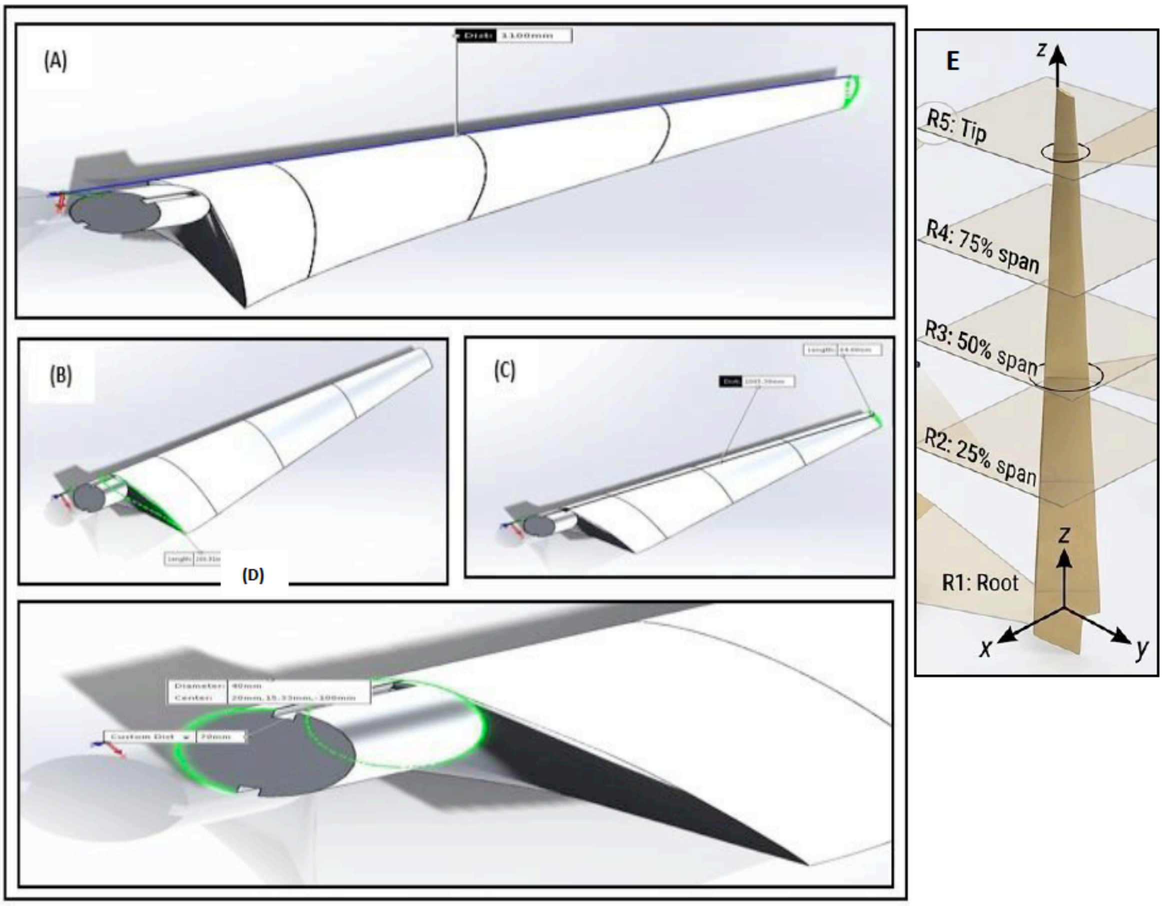

Figure 8: (A). The blade design with length of 1.1 m, varying sectional pitch angle **(B)**. The blade's chord width of 266.91 mm. **(C)**. The blade's Tip width of 64.88 mm **(D)**. The radius and length of blade Arm **(E)**. Schematic representation of varying sectional pitch angle.

Quantify the dimensional accuracy, the deviations from the design specifications were calculated for each feature using the formula:

$$\text{Deviation (\%)} = \frac{|\text{ Design value} - \text{Fabricated value }|}{\text{Design value}} \times 100$$

$$\text{Deviation in chord width (\%)} = \frac{266.91 - 260}{266.91} \times 100 = 2.58\ \%$$

$$\text{Deviation in blade length (\%)} = \frac{1100 - 1070}{1100} \times 100 = 2.72\ \%$$

The above equation computes the percentage difference between the measured value and design value thereby providing an indication of the level of precision achieved during fabrication. For all critical dimensions, the calculated deviations were found to be well within 2.8% of the design value. This does demonstrate high dimensional accuracy. Such precision ensures that the fabricated blade retains its intended aerodynamic profile and mechanical integrity, which are both essential and crucial to ensure efficient performance in wind turbine applications.

5. CONCLUSIONS

1. The present feasibility study on the fabrication of small-scale wind turbine blades using the conventional hand lay-up technique has demonstrated a practical approach for producing prototypes and components tailored for the purpose of research and small-batch production. The method offers significant flexibility in blade geometry, thereby enabling in the development and testing of various aerodynamic profiles for the purpose of optimizing turbine performance. By achieving high dimensional accuracy and maintaining structural integrity, the fabricated blades meet the design requirements essential for ensuring operational efficiency. More on the design can be found in our earlier work [22, 23].

2. A carbon fiber wind turbine blade, 1.07 m long with an arm length of 70 mm and radius 20 mm for hub insertion was successfully fabricated. The blade's chord width tapered from 260 mm at the root to 63 mm at the tip, closely matching software design. Overall dimensional deviations were well within 2.8%, confirming the efficacy of the hand lay-up process.

3. The fabricated blade's mass was around 380 g and volume of 682,981 mm³, resulting in a density of approximately 556 kg/m³, providing an indication of light weight structure that is suitable for low wind speed turbine operation [24]. This low density was achieved through the incorporation of internal support structures, such as ribs and spar, which does reduce material mass while maintaining structural integrity.

4. The study confirms the feasibility of producing dimensionally accurate, lightweight small-scale wind turbine blades using the hand lay-up method. However, future studies should focus on automating the process and assessing performance under real-world conditions.

ACKNOWLEDGEMENTS

The authors thank the Principal, B.M.S. College of Engineering, Bengaluru, Heads of the Department: Electrical & Electronics Engineering and Mechanical Engineering, for supporting the research activities. Thanks are due to the Dassault Systèmes La Fondation for their generous funding (DSF Contract ID: 52/2020, PROJECT ID-IN-2020-021), which made this research and development exercise possible. The authors express gratitude to M/s Cingularity TEC India Pvt. Ltd. (Bengaluru, India), for providing valuable industrial experience through internship opportunity for interested students. The overwhelming support rendered by the staff of M/s Cingularity TEC India Pvt. Ltd. (Mr. Samuel Gerald, Mr. Girish, Mr. Janardhan Naidu, and Mr. Sudheer) is acknowledged with thanks.

AUTHOR'S CONTRIBUTION STATEMENT

YSN, CHT, PNB, CHS – final year Electrical Department students carried out internship in M/s. Cingularity. Dr. Prema V. and Dr.Suhas B.G. worked on interdisciplinary project – guiding, drafting proposals and execution. Dr. Anil Chandra and Prof. T.S. Srivatsan oversaw drafting of manuscript.

CONFLICTS OF INTEREST STATEMENT

The authors declare no competing interests.

REFERENCES

[1] A. R. Anil Chandra and V. P. Nithin Kumar, M.Tech. Thesis, "Design and Fabrication of Wind Turbine Blade for Low Wind Velocity Areas," B.M.S. College of Engineering, 2021.

[2] J. D. Skramstad, "Evaluation of Hand Lay-Up and Resin Transfer Molding in Composite Wind Turbine Blade Manufacturing," Montana State University, 1999.

[3] L. Mishnaevsky, K. Branner, H.N. Petersen, J. Beauson, M. McGugan, B.F. Sørensen, Materials for Wind Turbine Blades: An Overview. Materials 2017, 10, 1285. https://doi.org/10.3390/ma10111285

[4] K. Scrivens and A. A. B. Abden, "Hand Lay-Up Technique for Manufacturing Composite Wind Turbine Blades," Renewable Energy, vol. 46, pp. 356-364, 2012.

[5] M. Das, "Study of Fiber Orientation Effects on Composite Wind Turbine Blades Fabricated by Hand Lay-up Process," International Journal of Advanced Manufacturing Technology, vol. 89, pp. 2563–2574, 2017.

[6] A. V. R. N. Kumar and S. S. Patil, "Fabrication and Testing of Small-Scale Composite Wind Turbine Blades using Hand Lay-Up Process," International Journal of Engineering Research & Technology, vol. 9, no. 6, 2020.

[7] M. A. Qureshi *et al*., "Mechanical Properties of Carbon Fiber Composite Wind Turbine Blades," Composite Structures, vol. 216, pp. 56-65, 2019.

[8] D. D. Suresh and P. K. Mishra, "Composite Materials and Manufacturing Techniques for Wind Turbine Blades: Review and Future Perspectives," Materials Today: Proceedings, vol. 21, pp. 223-230, 2020.

[9] J. M. C. Fernandes and J. G. Silva, "Effect of Hand Lay-Up Process Parameters on the Quality of Composite Wind Turbine Blades," Journal of Composite Materials, vol. 52, no. 5, pp. 687-700, 2018.

[10] Burton, T., Jenkins, N., Sharpe, D., & Bossanyi, E. (2011). Wind Energy Handbook (2nd ed.). Wiley. https://doi.org/10.1002/9781119992714

[11] M. Tahir *et al*., "Evaluation of Environmental and Health Impacts of Thermoset Resin Use in Wind Turbine Blade Fabrication," Journal of Cleaner Production, vol. 274, 2020.

[12] S. P. Singh and R. K. Jha, "Automation Challenges in Composite Wind Turbine Blade Production," International Journal of Automation and Computing, vol. 16, no. 4, pp. 347-356, 2019.

[13] T. Wang *et al*., "Fatigue Performance of Composite Wind Turbine Blades under Variable Load Conditions," Composite Structures, vol. 229, 2019.

[14] N. Gupta, R. K. Singh, and V. R. Suri, "Use of Natural Fibers in Composite Materials for Wind Turbine Blades," Materials Today: Proceedings, vol. 43, pp. 3574-3580, 2021.

[15] H. Zhao *et al*., "Vacuum Assisted Resin Transfer Molding for Wind Turbine Blade Manufacturing: A Review," Renewable and Sustainable Energy Reviews, vol. 113, 2019.

[16] P. M. Berto, J. G. L. Almeida, and S. L. Santos, "Impact of Fiber Volume Fraction on the Mechanical Properties of Composite Wind Turbine Blades," Composite Part B: Engineering, vol. 172, 2019.

[17] R. A. Khan and M. A. Wahab, "Post-curing Effects on Mechanical Properties of Epoxy Based Wind Turbine Blade Composites," Polymer Testing, vol. 80, 2019.

[18] A. S. B. Smith, "Environmental Considerations in Wind Turbine Blade Fabrication," Journal of Renewable Energy Engineering, vol. 45, pp. 141-150, 2020.

[19] J. R. Williams and D. G. Allen, "Effect of Lay-Up Sequence on Fatigue Resistance of Wind Turbine Blades," Journal of Composite Materials, vol. 55, no. 2, pp. 257-268, 2021.

[20] F. T. Johnson *et al*., "Development of High Strength Composite Blades for Offshore Wind Turbines," Composite Science and Technology, vol. 176, pp. 138-145, 2019.

[21] R. J. Ellis and L. D. Hartley, "The Use of Carbon Fiber Composites in Large-Scale Wind Turbine Blades," Materials Science Forum, vol. 943, pp. 243-250, 2018.

[22] Suhas, B.G., Sreejith, B.K., Chandra, A.R.A., Shivashankar R Srivatsa, V. Prema. Design of a low velocity wind turbine blades for power generation: part I-aerodynamic performance. Sādhanā 48, 276 (2023). https://doi.org/10.1007/s12046-023-02339-1

[23] Suhas B.G, Anil Chandra A.R, Prema V, Sreejith B.K., Abdulrajak B., Kiran Kumar K.U,. Effect of Boundary Layer Trips on Low-Velocity Wind Turbine Blade: A Computational Study,. International Journal of Mechanical Engineering, vol. 12, no. 3, pp. 28-35, 2025. https://doi.org/10.14445/23488360/IJME-V12I3P102

[24] R.H. Barnes, E.V. Morozov, K. Shankar, Improved methodology for design of low wind speed specific wind turbine blades, Composite Structures, vol. 119, 2015, pp. 677-684. https://doi.org/10.1016/j.compstruct.2014.09.034

https://doi.org/10.31875/2409-9848.2026.13.08