



WTB4: MODAL ANALYSIS OF WIND TURBINE BLADES BEHAVIOR WITH FOUR DISTINCT MATERIALS

Chandran Nagendran¹, Sathish Kumar K², and Venkatesan S³

¹ Department of Aeronautical Engineering, Nehru Institute of Engineering and Technology, Coimbatore, Tamil Nadu, India-641105.

Email:chandrannagendran008@gmail.com.

² Department of Aeronautical Engineering, Nehru Institute of Engineering and Technology, Coimbatore, Tamil Nadu, India-641105.

Email:Nietdrksathishkumar@nehrucolleges.com

³ Department of Design and Automation, Vellore Institute of Technology, Vellore - 632014. Email:venkatesans@vit.ac.in

<https://doi.org/10.30572/2018/KJE/170107>

ABSTRACT

To stay up with the constantly changing energy sector, wind turbine lifespan and energy efficiency must be increased. The advantages of the composite-material blade include low weight, high tensile strength, anti-corrosion, fatigue resistance, and thermal insulation. The selection of materials for wind turbine blades has been the subject of extensive research, particularly the comparison of metals and composites. Because of their characteristics, composites clearly produce better results than metals. However, there remains a research gap in determining which of the several composites is the best material. To examines the natural frequencies and associated deformation of four wind turbine blades composed of Kevlar, aluminium composites, Carbon Fibre Reinforced Plastic (CFRP), and Glass Fibre Reinforced Plastic (GFRP) this research work proposes WTB4: Modal Analysis of Wind Turbine Blades Behavior with Four Distinct Materials. This research goal also includes confirming the blade's strength and evaluating the aforementioned materials to determine which is most appropriate for a wind turbine blade and their vibration patterns. From the results, it is observed that the Carbon fibres provide stronger stiffness, lower compressive strength and a greater sensitivity to misalignment compared to other composite materials.

KEYWORDS

Fibre Reinforced Plastics (FRP), Aluminum Composites, Kevlar, Glass Fibre Reinforced Plastic (GFRP), Carbon Fibre Reinforced Plastic (CFRP), Wind Turbine Blades.



1. INTRODUCTION

A wind turbine is a revolving machine driven by wind. The nacelles, towers, and turbine blades are the three parts of a wind turbine. To support the weight of the generator, nacelles, and turbine blades, a wind turbine tower needs to be sturdy and long-lasting. Stiffness is the most important factor since the tower is susceptible to fluctuating wind loads due to the movement of the blades. Consider a nacelle as a house made up of supporting components such as generators, gearboxes, and shafts. Weight is more significant than material when it comes to Nacelles. The turbine blades must have an ideal cross section in order to be aerodynamically efficient and to deliver the highest torque that powers the generators. Variable wind loading causes the turbine blades to experience a variety of loads, such as tension, flapping, twisting and compression. Most crucial to a wind turbine system are its blades, which use wind energy to generate electricity. Wind loads caused wind turbine blades to deflect, thus it's important to balance a blade's weight and strength to avoid failure. These blades are very rigid and have a certain strength. Therefore, to lower the total weight of the wind turbine system and avoid fatigue failure of the turbine, sturdy and lightweight materials are needed. Drag and Lift are the two forces that the wind applies to turbine blades. The Drag Force travels parallel to the wind's direction, but the lifting force travels perpendicular to it. Lift force should be high and drag force should be minimal in order to generate the most power. The aim of this paper is to determine the natural frequencies and the accompanying deformation for four distinct materials such as Kevlar, Aluminum composites, Carbon Fibre Reinforced Plastic (CFRP) and Glass Fibre Reinforced Plastic (GFRP). Furthermore, verifying the blade's strength and assessing the previously mentioned materials to ascertain which is best for a wind turbine blade and their vibration patterns are the objectives of the analysis

The remaining portion of the paper is structured as follows: The problem statement and related work are compiled in Section 2. The modeling of wind turbine blades is explained in Section 3. The formulation for finite elements is shown in Section 4. Section 5 displays the performance evaluation of the suggested model, and Section 6 concludes with conclusions.

2. RELATED WORK

Determining suitable composites for designing the wind turbine blade plays a vital role in renewable source of power. Stimulated to move in this direction, this research work proposes Modal Analysis of Wind Turbine Blades Behavior with Four Distinct Materials. This section discusses the properties of wind turbine blades and advancement in determining the suitable composite for designing wind turbine blade. The impact of matrix cracking on the mechanical properties of FRP chips was investigated by ([Dookhi and Tahir, 2023](#)). In one-way glass fibre

reinforced polymer strips, the existence and lack of external cracks are investigated. (Alyousuf and Korkmaz, 2022) studied how Dual-Fed Induction Generator (DFIG) systems can be applied in a variety of ways to create intricate solutions. They presented the design and control of DFIG systems to enhance WT operating performance under various conditions. In the first plate, (Al-Maliky, 2018) examined the fibre and matrix, which were depicted as two distinct materials; in the second, a composite plate was displayed. While the grids and blades in (Thumthae and Chitsomboon, 2009) stayed stable with respect to the rotating frame, the conservation equations were numerically solved in a rotating frame. A new transition model that relies solely on correlation and local variables has been developed. The (Langtry., et al. 2006) validates the model for wind turbine transition forecasting. S. Tsai and C. H. Ong report that hybrid blades outperform the all-glass SERI-8 blade in terms of structural characteristics (Tsai and Ong, 2000). The aerodynamic principles of a contemporary wind turbine blade, such as the optimum angle of attack, blade planform shape and size, and aerofoil selection, were thoroughly explained (Schubel and Crossley, 2012; Khazem et al., 2019; D'Angelo and Timmer, 1995). A quick comparison of the wind tunnel test results for the airfoils DU 91-W2-250 and DU 93-W-210 was reported by (Halfpenny, 1998). The construction of a new frequency domain model that can evaluate fully flexible turbines using a Finite Element analysis method is described by (Krishnamurthy and Sesharao, 2017).

The dynamics of a horizontal wind turbine blade with NACA 63415 profiles based on centrifugal, gravitational, and aerodynamic loads are presented (Ramesh et al., 2017). In an effort to assess the performance of small wind turbine blade models using FEA, a blade profile for the NACA airfoil 63012A was created (Thrinadh et al., 2015). Two distinct materials are analyzed for wind turbine blades with twisted angles. The optimal blade model, determined by comparing two different wind turbine blade materials at twisted angles, was investigated (Deshmukh and Shekhawat, 2017). A preliminary design for a 50-meter-long blade was developed to evaluate cost and improve structural efficiency (Namiranian, 2011). Two versions of the blade were created: a carbon composite and fibreglass. The optimal design was found to maximise the cross-sectional area, chord length, and radius of gyration in order to achieve the maximum natural frequency (Yeh and Wang, 2017). To improve the aerodynamic performance of turbine rotors and reduce their sensitivity to wind gusts, rotor tips were modified to form winglets (Sarangi, 2014). Tilting the blade tip to produce a winglet effect by altering the downwash distribution was shown to reduce the generated drag and increase the power output (Abdullah, 2011). A 38-m-long blade with a rated power of 1.5 MW was developed using the BEM theory, and a chord distribution approach was also proposed (Abdullah, 2009; Abdullah

and Al-Ameen, 2007). Natural frequencies were computed using ANSYS, and the blade design was performed using the BEM theory (Abdullah, 2006; Negi, 2019). Pre-programmed software was utilised to optimise the blade geometry for wind turbine rotor design, with the objective of improving structural performance and reducing cost (Kabir and Ferdous, 2012). A 1.5 MW turbine rotor with a blade length of 35 m was designed using MATLAB programming (Igwemezie, 2018; Tengeri et al., 2018).

3. MODELLING OF WIND TURBINE BLADE

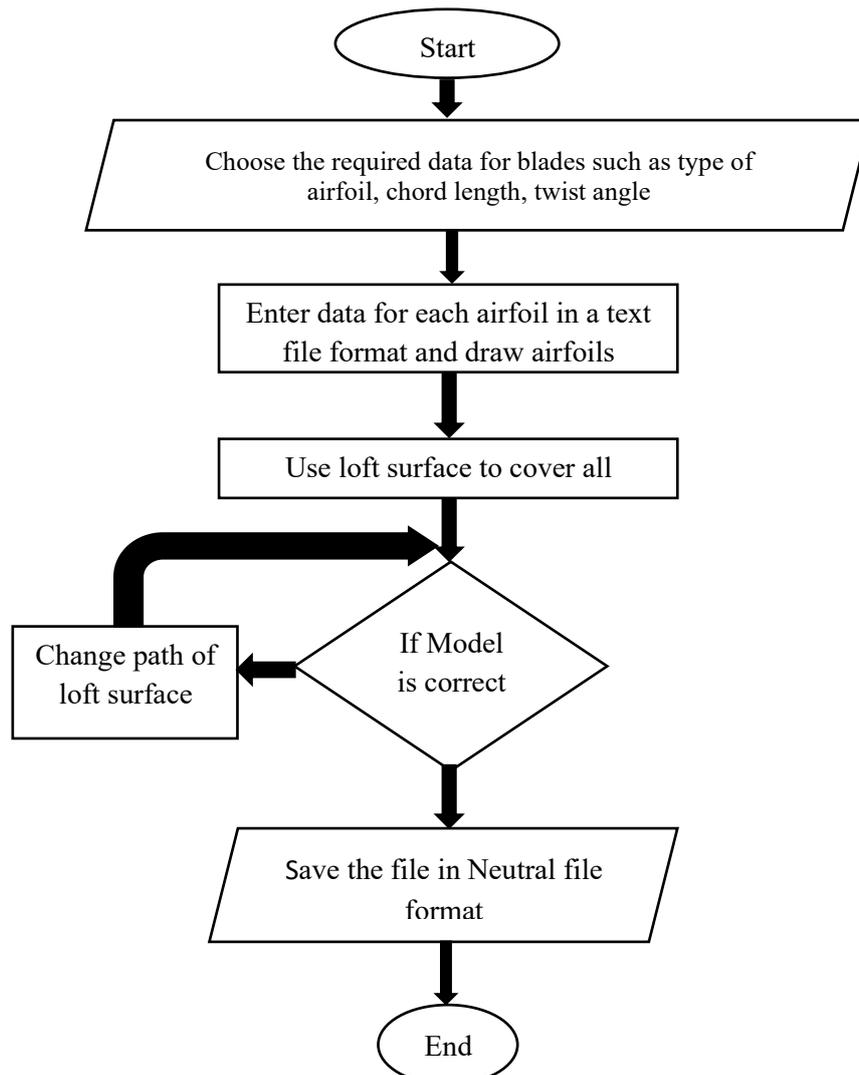


Fig. 1 Process flow diagram for creating a 3D model of a wind turbine blade

Using Creo, a 3D model of the blade of a wind turbine was created for this proposed work. The blade's length influences the thickness of its outer surface, which gradually drops from 40 mm at the blade root to 20 mm at the blade tip. The proper design of a wind turbine blade depends on the selection of the appropriate airfoils. DU and NACA64-618 series airfoil sections are used in this design, among others. The information for every airfoil was obtained from the airfoil tool website. These data may be converted from 2D to 3D using the EXCEL application, and

the files that are produced can be imported into Creo. The initial step in making the blade model is to draw the circle section on the appropriate plane at the origin point. The remaining circular and airfoil sections chosen for every blade location are then sketched. A three-dimensional model of the blade can be produced by lofting parts one after the other. To create a 3D model of a wind turbine blade, follow the steps shown in Fig. 1. Blades for wind turbines are designed to be resistant to fatigue and stiffness. As a result, extremely high-performance materials should be used to make the blades. Henceforth, composite materials like Kevlar, Aluminium Alloy, Carbon Fibre Reinforced Plastics (CFRP) and Glass Fibre Reinforced Plastics (GFRP) are preferred over other materials. The finite element formulation is presented in order to construct numerical models and address the vibration and steady-state issues. To examine the stresses caused by centrifugal force and free vibration, the 3D Blade model was loaded into ANSYS Workbench 2024.

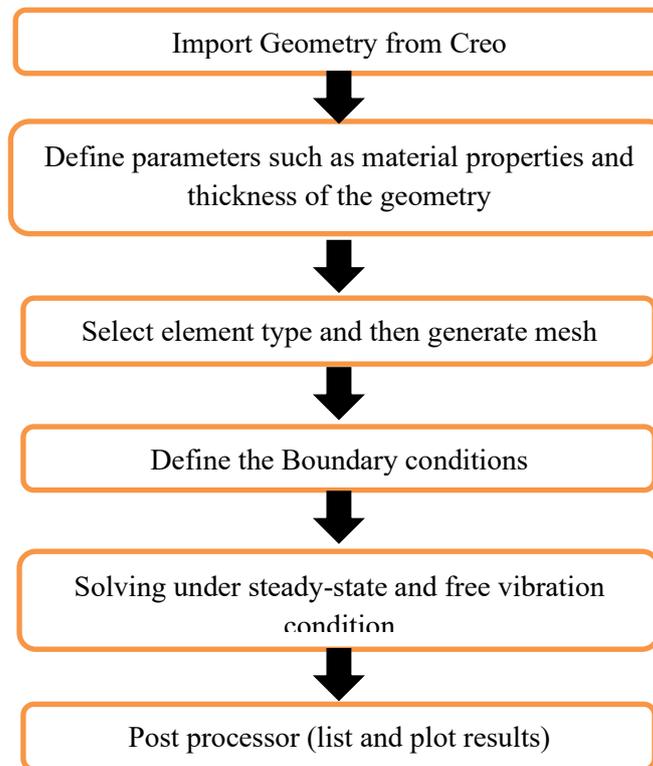


Fig. 2 Steps in Finite Element Analysis

In Ansys workbench 2024 the materials of the blade are mentioned by density, Young's modulus and Poisson's ratio. Examining the behaviour of a wind turbine's blade under several operating conditions is the main objective of the proposed work. The flow chart that describes the main phases of the finite element method applied to the modal and steady-state problems is displayed in Fig. 2. In order to represent the wind turbine blade, a cantilever beam with a fixed root end and a free tip was used. This study used four different materials namely Kevlar, Aluminum Composites, Glass Fibre Reinforced Plastic (GFRP) and Carbon Fibre Reinforced Plastic

(CFRP) to examine the effects of deformation on the wind turbine blade. In Ansys workbench 2024 the materials of the blade are mentioned by entering Density, Youngs Modulus and Poisson's ratio. The mechanical properties of the four materials are shown in Table 1.

Table 1: The mechanical properties of Kevlar, Aluminium Composites, CFRP and GFRP

Material	Density (N/mm ³)	Youngs Modulus (N/mm ²)	Poisson's ratio
Kevlar	1.4e-5	1.12e5	0.36
Aluminium Composites	2.6e-5	6.9e4	0.33
CFRP	1.6e-5	3.74e5	0.3
GFRP	1.8e-5	6.5e4	0.3

The following formula may be used to determine the wind turbine blades' steady state response:

$$\{R\} = [K]\{U\} \quad (1)$$

where the system's stiffness matrix is $[K]$, displacement vectors are represented by $\{U\}$, and load vectors (centrifugal force) are represented by $\{R\}$. The damping forces and inertia in Eq.1 were supposed to be equal to zero. When positioned correctly at $t=0$, a flexible structure can vibrate harmonically. At a frequency known as the Natural Frequency, the vibrations follow particular patterns known as mode forms, which are also referred to as deformation patterns. The mode shape and vibration of the structure are determined by its mass and rigidity.

4. RESULTS AND DISCUSSION

The current work used the finite element program ANSYS to design a wind turbine with a horizontal axis blade composed of different materials. A detailed analysis of the rotor blade's dynamic response, deformation mechanisms, and stress progression is made possible by this model. The distribution of stresses and deformations is clearly comparable across the four materials (the blade's tip region, where it moves freely, experienced the most deformation, whereas the root region experienced the largest stress). The materials' levels of stresses and deformations vary though aluminum composites had the lowest deformation value, followed by GFRP, CFRP, and Kevlar. The use of CFRP material clearly produced the lowest stresses.

Table 2: Natural frequency for the Blade with Distinct Materials

Natural Frequency (Hz)	Aluminium Composites	GFRP	Kevlar	CFRP
1	77.482	91.914	138.29	223.52
2	196.46	227.06	340.71	552.17
3	408.41	488.47	734.71	1187.9
4	1080.9	1287.6	1941.1	3131.3
5	1642.8	1956.6	2912.4	4758.1
6	1683.8	2005.1	2931.2	4876
7	2112.3	2559.5	3860.5	6224.2
8	3467.4	4181	6291.6	10167
9	4042.7	4982.1	7299.5	12116
10	4698.4	5474.9	8147.3	13314

Ansysis software was utilized to determine the 10 distinct natural frequencies of Aluminum composites, GFRP, CFRP and Kevlar. It is observed that every material shows a gradual rise until the third frequency, after which there is a sudden spike at the fourth frequency. The frequency then progressively increased once again until it reached the ninth level. Of the four materials, aluminum composites are the least common, followed by CFRP, GFRP, and Kevlar. [Table 2](#) lists the detailed values, and [Fig.3](#) shows them graphically. Each material has two peak locations, and the deformation of all the materials is akin to a waveform.

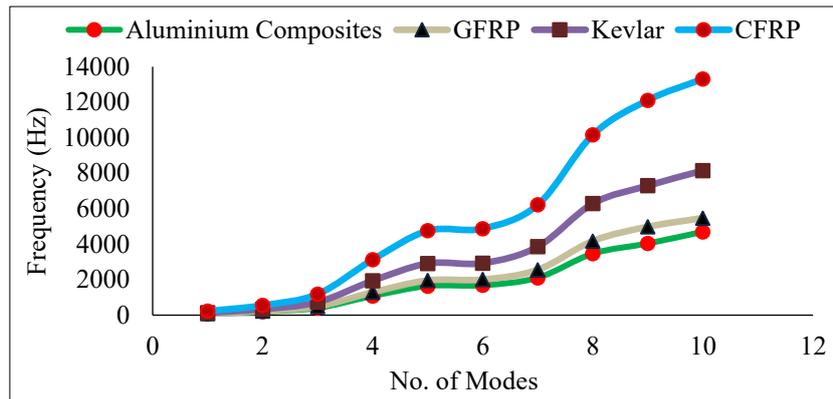


Fig. 3 Frequency Values for the Blade with Distinct Materials

The fifth and ninth modes show the highest deformation values for aluminium composites, whereas the sixth and ninth modes show the highest deformation values for GFRP, CFRP, and Kevlar. The detailed numbers are listed in [Table 3](#).

Table 3: Deformation Values for the Blade with Distinct Materials

Deformation (mm)	Aluminium Composites	GFRP	CFRP	Kevlar
Mode 1	13.8	16.53	16.76	18.73
Mode 2	12.38	14.85	15.05	16.84
Mode 3	14.62	17.68	17.93	20.03
Mode 4	15.21	18.26	18.51	20.91
Mode 5	22.96	18.22	18.48	24.72
Mode 6	14.77	27.64	28.02	28.13
Mode 7	17.32	20.25	20.53	22.93
Mode 8	16.53	20.54	20.83	23.93
Mode 9	28.68	35.42	35.91	40.52
Mode 10	15.63	18.79	19.05	21.31

The aluminium composites have the lowest deformation values when all the materials' deformation values are compared. The deformation values of CFRP and GFRP are comparable, albeit marginally greater than those of aluminium composites. Out of all the materials in this research, the Kevlar has the highest deformation value. Thus, it is evident that CFRP and GFRP deformation values fall between those of Kevlar and aluminium composites. As previously stated, all of the materials' deformation values exhibit a waveform pattern, although CFRP and GFRP exhibit the smoothest waveform. Therefore, the values of deformation for CFRP and

GFRP grow and drop somewhat, while those for Aluminum Composites and Kevlar increase and decrease rapidly shown in Fig. 4. For the wind turbine blades, therefore carbon reinforced plastic or glass fibre reinforced plastic can be employed instead of Kevlar and aluminum composites. Glass fibres are used in GFRP, whereas carbon fibres are used in CFRP. Compared to glass fibres, carbon fibres are lighter and stronger. Compared to GFRP, CFRP is more robust, lightweight, and long-lasting. Longer service life, reduced maintenance costs, and improved fuel efficiency can result from this. CFRP is more expensive than GFRP. GFRP is less harmful to the environment than CFRP.

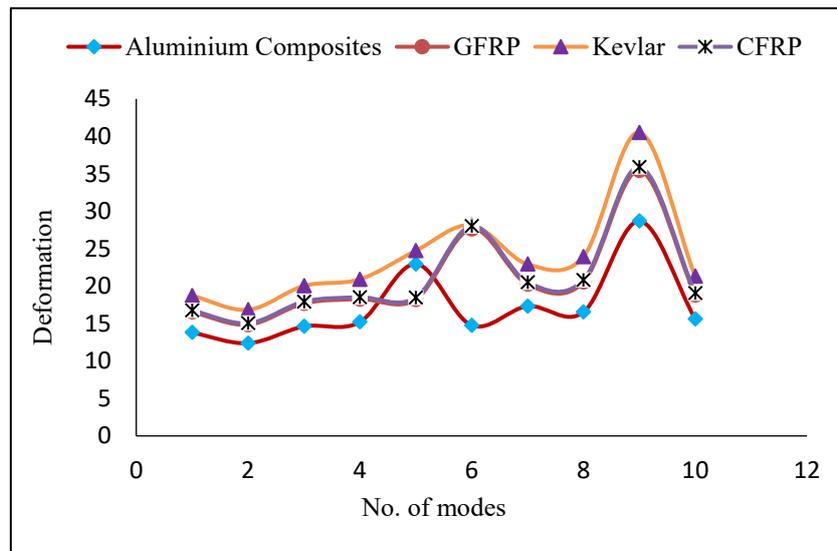


Fig. 4 Comparison of Deformation Values Between Four Materials

This is because the manufacture of carbon fibre requires more energy than that of glass fibre, and recycling CFRP is more challenging than recycling GFRP. Because of its low heat conductivity and strong specific resistance, GFRP is a common material in the construction sector. However, with abrupt contact, GFRP may be brittle and prone to breaking or cracking.

5. CONCLUSION

A composite wind mill blade was created and statistically examined as part of this project. The same load conditions are used to compare different composite materials. Stress, strain, and deformation are calculated using ANSYS. The frequencies and vibration modes of wind turbine blades, which range from first to tenth order are determined in this work by modal analysis. The point with high amplitude indicates the greatest deflection and failure probability. Since it is the part most subject to torsional and vertical pressures because of its distance from the hub, the blade tip frequently undergoes the most deflection. The centre of the blade indicates the minimal deflection area. The values of deformation for CFRP and GFRP grow and drop somewhat, while those for aluminum Composites and Kevlar increase and decrease rapidly.

For the wind turbine blades, we can therefore employ carbon reinforced plastic or glass fibre reinforced plastic instead of Kevlar and aluminum composites. Thus, it may be concluded from the properties, Characteristics, Frequency values and the deformation values for those corresponding frequencies, that Carbon Fibre Reinforced Plastics are a superior material for windmill blades. As an alternative to conventional aluminum composites, glass and carbon fibres show great promise. Carbon fibres ensure stronger stiffness but also offer lower compressive strength, higher costs, and a greater sensitivity to local defects (such misalignment). Several studies have shown that combining E-Glass and carbon fibres can result in both a lower cost increase and increased stiffness (from the carbon fibres).

ACKNOWLEDGEMENT

Authors have not received any fund to carry out this work.

CONFLICT OF INTEREST

Authors do not have any conflict of interest

6. REFERENCES

- Abdullah, O. (2006) 'Dynamic analysis of rotating cantilever plates', *Al-Khwarizmi Engineering Journal*, 2(2), pp. 46–60.
- Abdullah, O. (2009) 'Vibration analysis of rotating pre-twisted cantilever plate by using the finite element method', *Journal of Engineering*, 15(1), pp. 3492–3505.
- Abdullah, O. (2011) 'A finite element analysis for the damaged rotating composite blade', *Al-Khwarizmi Engineering Journal*, 7(1), pp. 56–75
- Abdullah, O. and Al-Ameen, E. (2007) 'Vibration of non-rotating blades: experimental and numerical investigation', *Journal of Engineering and Development*, 11(2), pp. 113–124.
- Al-Maliky, F.T. (2018) 'Numerical Investigation of Natural Frequencies for Clamped Longitudinal Composite Plates', *Kufa Journal of Engineering*, 10(1), pp. 92-110.
- Alyousuf, A.M. and Korkmaz, F. (2022) 'Performance Investigation of Wind Turbines Based on Doubly Fed Induction Generators with Back-To-Back Converter', *Kufa Journal of Engineering*, 14(1), pp. 1-12.
- D'Angelo, S. and Timmer, W.A. (1995) 'Two wind turbines dedicated airfoils tested in two different wind tunnels: comparison and results', *Windpower'95 Conference*, Washington DC, USA.

- Deshmukh, A.V. and Shekhawat, S.P. (2017) 'Analysis on wind turbine blade using composite materials', *International Conference on Recent Trends in Engineering and Science (ICRTES 2017)*, 6(1).
- Dookhi, M.A. and Tahir, A.A. (2023) 'Study the effect of external crack on the Mechanical Properties of Composite Materials', *Kufa Journal of Engineering*, 14(4), pp. 1-10.
- Halfpenny, A. (1998) *Dynamic analysis of both on and offshore wind turbines in the frequency domain*. PhD thesis, Faculty of Engineering, University of London.
- Igwemezie, V. (2018) 'Materials selection for XL wind turbine support structures: a corrosion-fatigue perspective', *Marine Structures*, 61, pp. 381–397.
- Kabir, R.B. and Ferdous, N. (2012) 'Kevlar – the super tough fibre', *International Journal of Textile Science*, 1(6), pp. 78–83. <https://doi.org/10.5923/j.textile.20120106.04>
- Khazem, Z., et al. (2019) 'Steady-state and vibration analysis of a Wind PACT 1.5-MW turbine blade', *FME Transactions*, 47(1), pp. 195–201.
- Krishnamurthy, T. and Sesharao, Y. (2017) 'Design and dynamic analysis of wind turbine blade', *International Journal of Innovative Research in Science, Engineering and Technology*, 6(9), pp. 18700–18710.
- Lagdani, O., et al. (2022) 'Modal analysis of an iced offshore composite wind turbine blade', *Wind Engineering*, 46(1), pp. 134–149. <https://doi.org/10.1177/0309524X211011685>
- Langtry, R.B., et al. (2006) 'Predicting 2D airfoil and 3D wind turbine rotor performance using a transition model for general CFD codes', *AIAA Paper 2006-395*.
- Namiranian, A. (2011) *3D simulation of a 5MW wind turbine*. Blekinge Institute of Technology, Sweden.
- Negi, A.S. (2019) 'A brief introduction to aluminum metal matrix composites', *Journal of Metallurgy and Materials Science*, 61(4), pp. 161–184.
- Ramesh, J., Kumar, P.R., Umar, M. and Mallikarjuna, M.V. (2017) 'Static and dynamic analysis of 1 kW small wind turbine blades by various materials', *Indian Journal of Scientific Research*, 17(2), pp. 161–165.
- Sarangi, S. (2014) 'Dynamic analysis of a wind turbine blade', *National Institute of Technology, India*.

Schubel, P.J. and Crossley, R.J. (2012) 'Wind turbine blade design review', *Wind Engineering*, 36(4), pp. 365–388.

Tenghiri, L., et al. (2018) 'Optimum design of a small wind turbine blade for maximum power production', *International Conference on Renewable Energies and Energy Efficiency*.

Thrinadh, D., Bandaru, S. and Venkatesh, P.H.J. (2015) 'Static and dynamic analysis of wind turbine blade', *International Journal of Engineering Technology Management and Applied Sciences*, 3, pp. 39–45.

Thumthae, C. and Chitsomboon, T. (2009) 'Optimal angle of attack for untwisted blade wind turbine', *Renewable Energy*, 34(5), pp. 1279-1284.

Tsai, S. and Ong, C.H. (2000) 'The use of carbon fibre in wind turbine blade design: a SERI-8 blade example', *Sandia National Laboratories Report*, 2000-0478.

Yeh, M.K. and Wang, C.H. (2017) 'Stress analysis of composite wind turbine blade with different stacking angle and different skin thickness', *Conference on Materials Science and Engineering Application*, ISBN 978-1-60595-448-6.