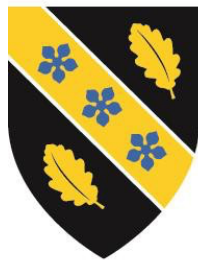


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Manufacture of Wine Turbine Blade

ACMA6000 – Advanced Processes and Materials

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Executive Summary

This report considers the stages of wind turbine blade development from design to manufacture and performance through weighted decision making and recognised equations. The report integrates aerodynamic design, material selection, manufacturing route analysis, and structural consideration.

The parameters of the report include 12 m/s wind speed, an air density of 1.225 kg m^3 NACA 4412 aerofoil, a power coefficient $C_p = 0.40$ and lift coefficient $C_l = 1.20$. The design of the blade was to be 50m with 5 sections.

Engineering principles are considered throughout the report, providing thorough evaluation of material selection and aerodynamic preferences. This uses mechanical properties as a comparative metric to achieve the optimised material for the application of the turbine blade.

Failure modes such as fatigue are also analysed and calculated with preliminary formula and equation used as a guide for top-level analysis.

1.0 Introduction

The development and progression of wind turbine technologies is a necessary endeavour in finding efficient methods of electricity generation. As dimensions and power ratings are identified and scrutinised, demand for improved aerodynamic performance, structural make-up, and manufacturing ease create an opportunity to find optimised rotor blades to achieve effective performance.

As alternative energy sources become an important part of our national grid and energy security, progression of performance is key to resolve energy crisis and power losses. Desired mechanical properties must be considered throughout the implementation and use of wind turbines to provide an effective design and manufacture process that performs as required in onshore and offshore applications. Harsh environments in high altitude, corrosive, and wet areas create external variables for blade development.

The optimal design and performance of wind turbine blades is held back by both the laws of energy losses and momentum theories, but also by the technologies available to us in industry today. Whilst development of the turbine blades has been enhanced from manufacturing techniques available through the last decade, high costs of material, testing, and design mean that trade-offs are required to feasibly use enhanced turbine blades.

2.0 Literature Review

Wind Power and Aerodynamic Efficiency

The power produced from the wind turbine can be shown with the formula below for a uniform air stream:

$$P_{Wind} = \frac{1}{2} \rho A V^3$$

The wind power produced considers the variables of ρ (air density), A (swept area), and V (wind velocity). The formula used at this stage is very basic and does not consider several key variables in its performance.

The useful aerodynamic power that is harnessed from the rotor is:

$$P_{Turbine} = C_P P_{Wind}$$

As shown in the previous formula, the velocity of the wind plays a crucial variable in P_{Wind} . A small increase in wind velocity leads to a large change in power produced. Despite this, the turbine is unable to extract the entirety of the kinetic energy due to further energy losses through factors such as heat and vibration. (*Karam Maalawi, 2022*).

The Betz limit refers to the ideal maximum power coefficient. A coefficient of $C_p \leq 0.4$. This can be used as part of a preliminary calculation.

$$A = \pi(50m)^2 = 7,853.98 m^2$$

$$\begin{aligned} P_{Wind} &= \frac{1}{2} (1.225) (7,853.98) (12)^3 \\ &= 8.31 MW \end{aligned}$$

$$\begin{aligned} P_{Turbine} &= (0.40)(8.31) \\ &= 3.326 MW \end{aligned}$$

This provides an approximate value of 3.33 MW that is achieved aerodynamically, prior to the losses caused through drivetrain and electrical variables. Whilst this

calculates the aerodynamic properties, the energy produced during a year cannot be predicted from this. Continuous wind speed changes make a true value of efficiency and performance difficult to analyse in this scenario. (*Martin, 2013*).

Tip-Speed Ratio and Rotational Speed

The tip-speed ratio, in this application, refers to the ratio at which the speed of the blade tip at the tangent in relation to free stream wind speed.

$$\lambda = (\omega R)/V$$

The angular velocity can therefore be worked out from the formula with the rearrangement showing:

$$\omega = (\lambda V)/R$$

The following values assigned to the formulas above provide a theoretical value for the angular velocity (ω), along with the rotor speed (N) in revolutions per minute.

$$\omega = (7 \times 12)/50$$

$$\omega = 1.68 \text{ rad/s}$$

$$N = \frac{(\omega \times 60)}{2\pi}$$

$$N = \frac{(1.68 \times 60)}{2\pi}$$

$$N = 16.04 \text{ rev/min}$$

The values calculated from the working above are used to calculate the corresponding blade-tip velocity:

$$V_{tip} = \omega R$$

$$V_{tip} = 1.68 \times 50$$

$$V_{tip} = 84.0 \text{ m/s}$$

The tip-speed ratio being high allows for a high transfer of energy from narrow and slender blades, whilst also providing an effective aerodynamic profile. Excessive tip speed, however, impacts noise levels, leading edge erosion, along with centrifugal loading on the rotor and structure. This analysis is crucial to avoid mechanical and structural failures at component fixtures and material. (*Martin, 2013*).

NACA 4412 Geometry

$$y_t = 5tc \left[0.2929 \sqrt{\left(\frac{x}{c}\right)} - 0.1260 \left(\frac{x}{c}\right) - 0.3516 \left(\frac{x}{c}\right)^2 + 0.2843 \left(\frac{x}{c}\right)^3 - 0.1015 \left(\frac{x}{c}\right)^4 \right]$$

This formula is used to show the NACA 4412 four-digit cambered aerofoil. This standardises the profile of the blade for required chord lengths and thicknesses. The profile of the blade requires a change of size and thickness as it moves closer to the blade tip. The maximum camber is 0.04c, with this maximum camber location being set at 0.4c, 40% along the entire section of the chord. The maximum thickness of the blade is 0.12c. The thickness distribution is NACA standard is shown in the formula above, with x expressed as a fraction of the blade chord.

The above equation provides the coordinate data required to create a coordinate-based CAD loft section. The thickness profiles were taken at $r/R = 0.2, 0.4, 0.6, 0.8$ and 1.0 . Due to the same NACA 4412 profile being used throughout the blade, the sections are scaled along each local chord. Whilst the report considers one profile, industry produced designs can include several thickness profiles throughout the blade chord to achieve an optimised aerodynamic profile. This would likely produce a blade with great structural thickness at $r/R = 0.2$, and sections closer to r/R being aerodynamically thinner. (*Sheikh, 2019*).

Lift to drag ratio

The lift and drag for aerodynamic performance can be shown with the formulas below:

$$L = \frac{1}{2} \rho V_{rel}^2 A_s C_l$$

$$D = \frac{1}{2} \rho V_{rel}^2 A_s C_d$$

The relative flow velocity V_{rel} and reference area of the blade A are variables as part of the formula. The aerodynamic efficiency can be calculated from the formula below:

Aerodynamic Efficiency:

$$L/D = C_l/C_d$$

The lift being a high value is required to provide a dominant tangential force to create initial angular velocity. Drag ultimately uses the negative pressure to oppose positive rotation. In application, both the lift and drag are subject to Reynolds number, angle of attack, and surface roughness. This makes the fixed values only suitable to initial calculations. (Sheikh, 2019).

Fatigue and Environmental Loading

Fatigue control must be considered throughout the manufacture and application of the blades. The blade will undergo millions of variable load cycles, with changing external forces caused by turbulence, wind shear, yaw error, tower shadow, and gravity. These variables must be considered alongside static stresses to ensure that the ultimate strength considers the additional forces present on the blade. The fibre make-up of composites makes them effective as the fibres can be aligned to with principal loads. Manufacturing for these materials must be effective in avoiding voids, material waviness, and adhesive gaps. Once in the application, the material will be subject to leading edge erosion, moisture and temperature cycles, and ultraviolet exposure. The materials tolerance to damage and suppressing the propagation of material defects must be aligned with the manufacturing quality and tensile strength. (Callister, 2014).

3.0 Design Specifications

Rotor Radius R	$50m$
Wind Speed V	$12m/s$
Air Density ρ	$1.225kg/m^3$
Power coefficient C_P	0.40
Lift coefficient C_l	1.20
Tip-speed ratio λ	7
Aerofoil	$NACA\ 4412$
Root-section Chord	$0.40m$
Tip chord	$0.10m$

r/R	Radius r (m)	Chord c (m)	Maximum thickness $0.12c$ (m)	Maximum camber $0.04c$ (m)	Camber position $0.04c$ (m)
0.2	10.0	0.400	0.048	0.016	0.160
0.4	20.0	0.325	0.039	0.013	0.130
0.6	30.0	0.250	0.030	0.010	0.100
0.8	40.0	0.175	0.021	0.007	0.070
1.0	50.0	0.100	0.012	0.004	0.040

Figure 1 - Table of geometric proportions of the turbine blade from NACA 4412 profile.

The profile of the blade is derived from the NACA 4412 profile, with above values used to generate the geometrical properties of each section at $r/R = 0.2$ through to $r/R = 1.0$. Whilst the values above follow the profile and coordinates fully, a developed model would likely use more than one profile as the blade moves to the sections nearer the tip. This can also be said for the blade root section, where the chord may be too slim for the application of the 50m blade.

4.0 Material Selection

Material selection for the application of a wind turbine blade requires the consideration of several mechanical and economical properties. Material properties considered for their use in this application included tensile strength, fatigue limits, cost, manufacturability and sustainability. With each material having variable properties based on grade, fibre structure and production processes, the comparison between materials includes varying upper and lower limits of material properties.

Material	Density (kg/m ³)	Young's modulus (GPa)	Tensile Strength (MPa)	Notes
Aluminium alloy	2700	69	250-270	Recyclable and easily manufactured.
Carbon steel (Structural steel)	7850	200	400-1000+	High rigidity, low cost. High mass reduces lift and initial velocity.
Silicon carbide	3150	400	200-500	High rigidity and wear resistance. Low fracture toughness limits use as primary material for application.
GFRP / Epoxy	1900	40 (longitudinal)	500-1000+ (longitudinal)	Low density, high fatigue resistance for lower cost, difficult to recycle.
CFRP / Epoxy	1500	70-150+ (longitudinal)	800-2000+ (longitudinal)	High stiffness for application, high material cost and difficult to recycle material.

Figure 2 – Comparative table of material properties and behaviours (Kutz, 2002).

Based on the available values and data of the materials in contention, CFRP shows several key material properties that are desirable for a turbine blade. The mechanical properties of the GFRP also align with the demands of the application of the turbine blade, making it suitable for use in the blade. GFRP has similar strengths and limitations as the CFRP, with similar properties such as strength, stiffness and fatigue resistance. The key difference between the two are the cost and manufacturability,

with GFRP being cheaper and easier to work with as a material. Based on these findings, a hybrid solution would be the most effective. GFRP would be effective for shells, whilst in regions that require greater longitudinal stiffness for deflection and mass, the structural benefits of CFRP can be used. This provides a strong blade with high mechanical benefits, whilst limiting expense of having an entire blade made from CFRP. (*Kutz, 2002*).

5.0 Exploration of Manufacturing Routes

Metals: Casting and Extrusion

Molten alloy is poured into a mould to create complex shapes in metal casting. This can produce a variety of components when molten metal is solidified, fettled, heat treated, and machined. Whilst effective in several application, defects often occur in shrinkage, porosity, and dimensional inaccuracy. (*Groover, 2011*).

Extrusion is when a die is used to force a heat billet to create a continuous cross-section. Whilst effective in producing longer, consistent shapes, the blade's changing chord size and angle of twist make it ineffective to manufacture with this technique. A metal blade would increase mass and fatigue concentration areas where joining would be required through welding along with other techniques. (*Schwartz, 2010*).

Ceramics: Powder processing and additive manufacture

Manufactured ceramics use powders that are sintered to create a dense ceramic component. Ceramics have high hardness and stiff, whilst also being able to tolerate high temperatures. This process often suffers with shrinkage, porosity, and brittle fracture. Due to the difficulty of producing a 50m blade, the use of ceramics is not viable, and would not work in this application. Whilst ceramics could be considered for the base or other elements relating to the wind turbine, it is unrealistic that it would ever be effective as a blade. (*Groover, 2011*).

Polymer Composites: vacuum-assisted resin infusion

Vacuum-assisted resin infusion is the most effective manufacturing route for the proposed blade design. The comparison of CFRP and GFRP to other materials makes this manufacturing route the obvious candidate for blade manufacture.

For this manufacturing to be effective, the process begins by laying dry reinforcement and the core materials into a mould, then sealed with peel ply and sealed vacuum bag. This is then evacuated and leak tested, before lastly being infused with a low viscosity resin. After the complete 'wet out', the laminate will be cured before demoulding the material, and performing final trimming, finishing and final inspection. This type of manufacturing for wind turbine blades has been used for a long time in the industry, making it the expected and necessary manufacturing route. (*Ray et al., 2024*).

The quality of this process is critical to avoid local stress concentrations and bond defects. Several defects can be common in this process, such as voids, fibre waviness, and incomplete cure. Ensuring that the process controls the resin viscosity and temperature, uses effective inlet and vent positions, looks for any vacuum leak testing, and uses extensive non-destructive testing techniques ensures an effective and accurate process. (*Janak, Teli and Raikar, 2017*).

6.0 Cost Evaluation

The cost of design, manufacture, transport, installation, and maintenance are subject to several variables and external factors. Each one of the costs have increased throughout the last decade and will continue to in decades to come. The overall cost for the turbine blade is approximately £50,000.00 to £200,000.00. An accurate estimate is difficult to achieve, as to quote accurately factors such as location for transportation, detail of on-shore or off-shore activity, manufacturing companies able to make the blade, along with many more factors. (*Wiesław Ostachowicz et al., 2016*).

Material cost can be made comparative, with the following table giving an estimate price list based on potential materials for consideration.

Material	Density (kg/m ³)	£/kg (Estimate, subject to supplier quotation)	Mass at 10m ³	Raw material cost
Aluminium	2700	£3.00	27000	£81,000
Silicon carbide	3200	£10.00	32000	£320,000
GFRP	1900	£5.00	19000	£95,000
CFRP	1550	£20.00	15500	£310,000.

Figure 3 - Table with comparative costs and density for candidate materials (*Kutz, 2002*)

Whilst the values of density and price are approximate due to varying grades and types of material, this information provides key consideration in material selection and procurement. The chosen material hybrid of CFRP and GFRP in justified with the approximate prices provided above, with an entire blade from CFRP being significantly more expensive than the hybrid solution. (*Karam Maalawi, 2022*).

This analysis only considers the density of the material, which does not consider the equivalent stiffness, fatigue life, and allowable loads that happen at different density volumes for different materials. The low density of CFRP is attractive for the application, where reduced weight provides better lift of the blade during the turning of the blade.

The manufacturing costs of the CFRP and GFRP moulding are also considered, where mould occupancy, labour, and energy will contribute to the overall cost. The additional cost for the material requires improved processes in accuracy and waste management to ensure as little as possible is lost in defects and material wastage.

7.0 Mechanical Properties Analysis

Section relative velocity

Without considering induction and yaw, a simplified local relative velocity can be estimated considering the factors of axial wind speed and tangential speed:

$$V_{rel}(r) = \sqrt{V^2 + (\omega r)^2}$$

With $V = 12\text{m/s}$ and $\omega = 1.68\text{ rad/s}$, the relative velocity increases moving towards the tip of the blade.

Lift and drag at each spanwise station

$$L = \frac{1}{2} \rho V_{rel}^2 A_s C_l$$

$$D = \frac{1}{2} \rho V_{rel}^2 A_s C_d$$

$$A_s = c \Delta r$$

At each 10m section corresponding r/R , the lift and drag can be calculated and considered with relative velocity from the chord length and area of the cross section at each cross section.

r/R	R (m)	C (m)	V_{rel} (m/s)	Lift L (N)	Drag D (N)
0.2	10	0.400	20.65	1253	20.9
0.4	20	0.325	35.68	3041	50.7
0.6	30	0.250	51.81	4932	82.2
0.8	40	0.175	68.26	5994	99.9
1.0	50	0.100	84.85	5292	88.2

Figure 4 - Turbine blade dimensional properties adhering to the NACA 4412 profile

The calculations for forces show preliminary values calculated from formulas shown in the first section of the report. For a full BEM solution to be conducted, induction factors, local inflow angle, angle of attack, twist, Reynolds-dependant aerofoil data, along with tip / root loss corrections.

Root bending moment and bending stress

For preliminary beam bending:

$$\sigma = My / I$$

For the preliminary calculation, the M root is estimated to be 725,660 Nm based on the M root formula below:

$$M_{root} = \Sigma(L_i r_i) \\ \approx 725,660 \text{ Nm}$$

Assume second moment of area $I = 0.015m^4$ and $y = 0.25m$

$$\sigma = \frac{725,660 \times 0.25}{0.015} \\ = 12.09 \text{ MPa}$$

If an allowable predicted stress of $\sigma = 250 \text{ MPa}$ is allowed:

$$FoS = \frac{250}{12.09} \\ = 20.67$$

This does not consider the dynamic stresses that act on the blade such as buckling, fatigue and joint assessment. This requires a validated finite stress model to ensure that all dynamic stress and forces acting on the blade are factored in to ensuring that the blade withstands the forces and remains within its desired factor of safety. (Hansen, 2013).

Torsional Loading

A thin closed wall section of the blade has a shear flow relation that can be shown from the formula:

$$q = T / (2A_m)$$

The wall shear stress derived from this can be shown from:

$$t = q / t_w \\ t = T / (2A_m t_w)$$

A_m represents the hollow area within the median wall line, where t_w represents the wall thickness. The torsional efficiency of a closer blade shell is illustrated from the equation. Shear stiffness and coupling effect is required for real composite torsion. (Hansen, 2013).

8.0 Comparative Analysis

Mechanical Property	Metals	Ceramics	GFRP CFRP composites
Density	Moderate to High	Moderate	Low
Stiffness	Moderate	High	Very high
Fatigue Resistance	Moderate	Poor	High
Impact tolerance	High	Poor	Moderate
Large complex aerofoil manufacture	Impractical	Impractical	Established
Defects	Porosity, weld defects, distortion	Porosity, cracking, shrinkage	Wrinkles, dry spots, voids
Recyclability	High	Moderate	Low
Overall blade suitability	Moderate	Poor	Strong

Figure 5 - Comparative matrix for decision of material selection.

The above table gives a general comparison of several of the material properties desired for the production of a wind turbine blade. The results show the overall desired material being the GFRP and CFRP hybrid material, as it shows low density, high stiffness and fatigue resistance, along with the manufacturing of the application previously developed in the same material process. This ensures that there are several manufacturing options as it does differ from what is currently produced. Quality control is necessary to ensure accuracy and effectiveness of production, especially considering the potential defects and issues that can occur from poor practise. As the properties align with the CFRP and GFRP for manufacture, its performance in the application is by far the most effective. Low density and high rigidity promote high lift to drag ratio, whilst providing the most effective blade for tip speed and energy production. (Schwartz, 2010).

The issue of recyclability is not new for composites, with it being a continued issue in the industry of manufacturing and energy production. With the life span of the blades up to around 15 years, the issue of recycling and re-using these materials becomes

difficult and financially expensive. As material science continues to develop its understanding of composite usage, the adoption of recyclable resin and thermoplastic composites will continue to create more effective materials. Wind energy is often advertised as a clean source of energy; however, the aftermath of material that cannot be re-used and recycled makes it difficult to sell the principle to investors and governments that they are in fact 'clean'.

A 3D perspective view of a tapered wedge. The object is light gray with a thin black outline. It has a rectangular base and a top surface that tapers to a point. The front face is a trapezoid. The object is positioned diagonally on a light blue background. In the top right corner, there is a small 3D coordinate system icon with axes labeled X, Y, and Z. In the bottom left corner, there is a small green icon of a person.

[illegible]

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r/R	R (m)	C (m)	Max thickness (m)	Max camber (m)	Twist (deg)
0.2	10	0.400	0.0480	0.0160	14.00
0.4	20	0.325	0.0390	0.0130	11.00
0.6	30	0.250	0.0300	0.0100	8.00
0.8	40	0.175	0.0210	0.0070	5.00
1.0	50	0.100	0.0120	0.0040	2.00

Figure 8 - Dimensional properties of blade based on geometric points of NACA 4412 profile.

10.0 Conclusion and Recommendations

This preliminary report has demonstrated the balancing act required to determine the correct processes and materials to use in the application of a wind turbine blade. There are trade-offs throughout the analyses process of this application, with aerodynamic performance, structural, manufacturing, and lifecycle considerations.

This report has assumed a 50m radius at 12m/s, the swept area is 7,8553.98 m² with an available wind power of approximately 8.31 MW. Approximately 3.33 MW is extracted aerodynamically based of a CP of 0.40. A TSR of 7 means the rotor spins at 16.0 rpm, the blade-tip speed is 84 m/s.

The comparative analysis of the material candidates identified CFRP and GFRP as the favoured material for usage in this application. Their low density paired with high rigidity and strength makes them desired for the application of a wind turbine blade. The hybrid material mixture ensured that the cost could be reduced as opposed to the expense of a full CFRP. The defects involved in the vacuum assisted resin infusion makes accuracy and effect manufacture essential to avoid failure in the material. Ensuring that vacuum integrity, resin-flow control, and non-destructive testing is used is vital.

The report details appropriate calculations and formulas for a very high-level analysis. For detailed design and manufacture, further detail and effect research is necessary. To progress the detailing required to implement this into design blade-element momentum theory would need to be considered, along with optimal twist and chord, laminate theory, and fatigue and buckling analysis.

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