

University of Wales Trinity Saint
David
School of Engineering



Manufacture of Wind Turbine Blade
Advanced Processes and Materials
ACMA6000

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Abstract

This report presents the material, design and manufacture of a next generation wind turbine blade intended to support renewable energy generation for Pentrehafod school. The study evaluates aerodynamic profiles, blade geometry, material selection, manufacturing processes, mechanical performance and cost considerations to identify the most suitable blade design. Analysis of several aerofoil profiles determined that the NACA 2412 aerofoil provided the most favourable lift to drag characteristics across a wider range of operating conditions. A blade length of 6.5 m was selected achieving above the required energy output while remaining economically viable. Material assessment using a weighted decision matrix compared metals, ceramics and composite materials, identifying carbon fibre reinforced polymer (CFRP) as the optimal choice due to its high strength-to-weight ratio and superior fatigue resistance. Manufacturing route evaluation concluded that vacuum infusion is the most appropriate process for large composite blade production, providing high-quality laminates with relatively low tooling cost. Mechanical analysis demonstrated maximum bending and torsional stresses of 9.36 MPa and 0.088MPa under extreme wind conditions, remaining well below CFRP material limits. It is therefore recommended that a CFRP blade manufactured using vacuum infusion be adopted, with future work focusing on FEA analysis, fatigue validation and sustainability improvements.

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1 Introduction

This report develops the next-generation wind turbine blade that will enhance the energy output performance and minimize maintenance costs. Focusing on aerodynamic design parameters, materials selection, mechanical performance analysis, manufacturing processes, defects, and cost evaluations with a summary of findings and a final blade design. Metals, ceramics, and polymer composites are critically compared to determine the most advantageous solution to ensure that the blades are lightweight, durable, and as sustainable as possible. Wind energy has become one of the most important renewable energy sources due to increasing environmental concerns with fossil fuels and the ambitious 2050 net zero CO₂ emissions target set out by the United Kingdom as stated by Climate Change Committee (2025). The efficiency and durability of the turbine blades are strongly influenced by the blade's geometry, material and the manufacturing technique used. Modern wind turbine blades are require meeting several requirements simultaneously. They must be lightweight to reduce gravitational loading, stiff enough to prevent excessive deflection, be resistant weather and environment degradation. Have the capability to resist fatigue caused by cyclic wind loading, while remaining economically viable to manufacture and operate.

2 Literature Review

2.1 Aerodynamic Profiles

The U.S Department of Energy (2023) states wind turbine blades are designed using aerodynamic aerofoil profiles to maximise lift. These profiles improves aerodynamic performance and structural durability of the blades. There are several aerofoil profiles, including NACA 6412 *Figure 1*, NACA 6409 *Figure 2*, NACA 4412 *Figure 3*, NACA 2412 *Figure 4* and many more. By reviewing Hossain et al, (2014) experimental results in *Table 1* shows that NACA 4412 with a lift-to-drag ratio of 5.382 at 5° is greater than 6409 that achieved 0.66, later experiments in blade design by Gok and Alnimer (2024) indicate that NACA 2412 has a greater range in lift-to-drag ratio than NACA 4412 across the range of angle of attack , this can be seen in *Figure 5*. Further reviews indicate that profiles like NACA 6412 can provide even greater lift, but the stability of the blade will be decreased if used as the core profile of a large blade (Tira and Furqon, 2024). Further research and analysis can be seen in Appendix A.

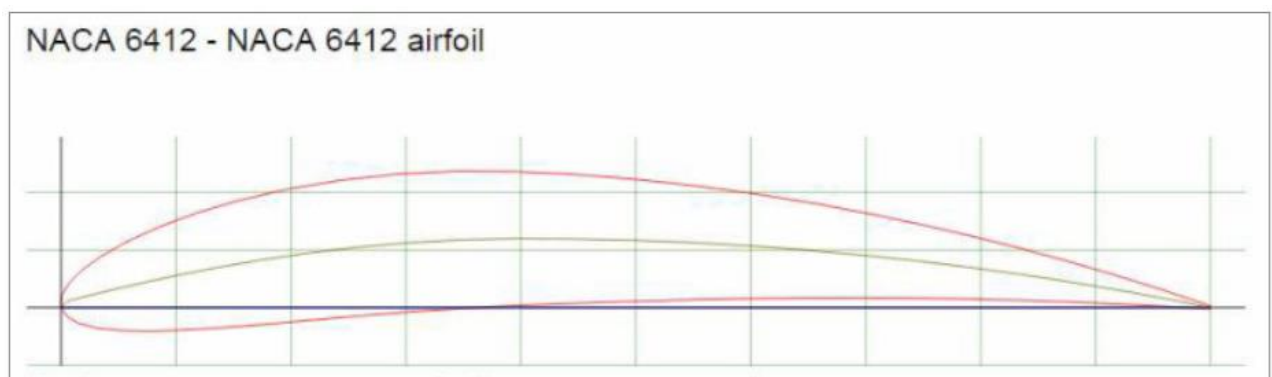


Figure 1 - NACA 6412 Profile (Santos et a.,2016)

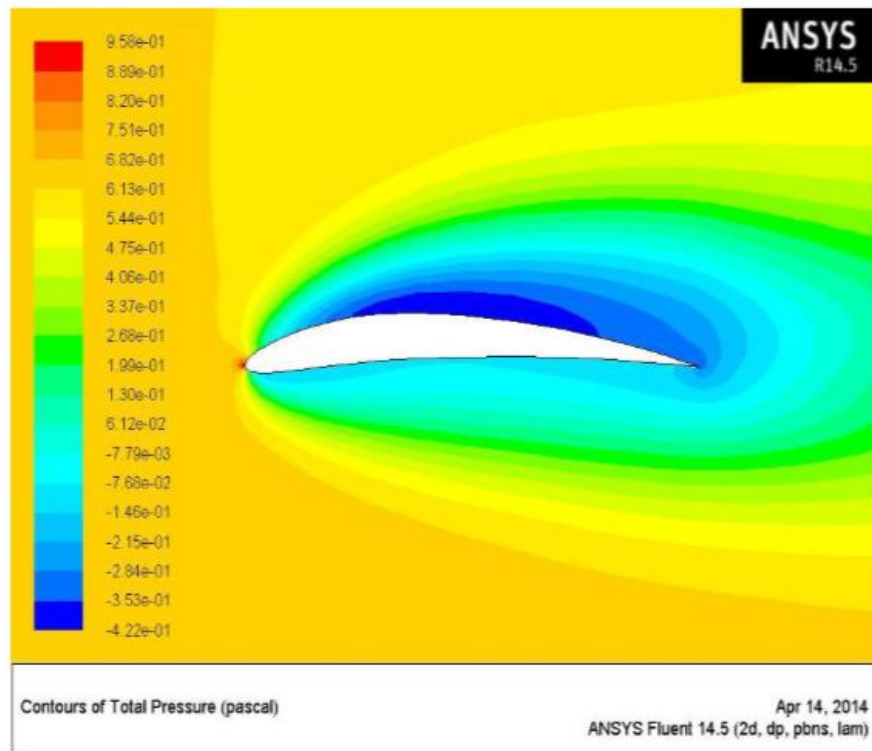


Figure 2 – NACA 6409 Profile and pressure distribution at 5° Angle (Hossain et al, 2014)

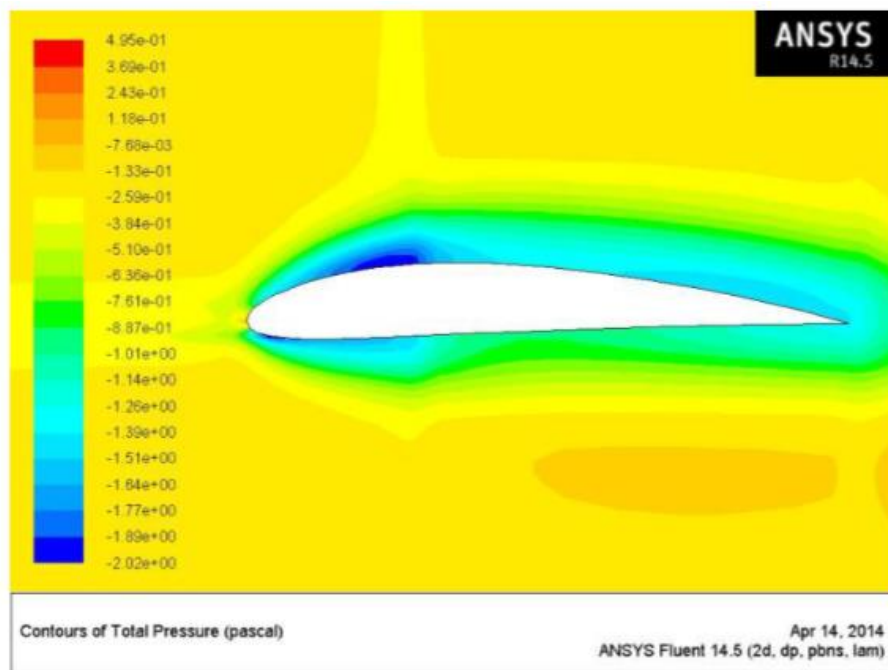


Figure 3 – NACA 4412 profile and pressure distribution at 5° Angle (Hossain et al, 2014)

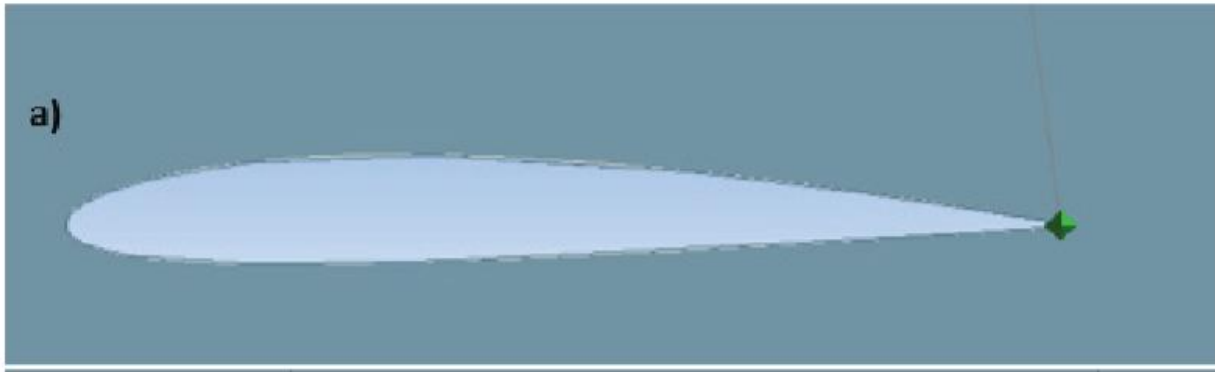


Figure 4 - NACA 2412 profile (Gok and Alnimer, 2024)

A high lift to drag ratio is desirable because greater aerodynamic lift can be generated relative to the opposing drag, therefore increasing the torque available for greater power output.

Table 1 – Lift to Drag Ratio NACA 4412 and NACA6409 (Hossain et al, 2014)

Angle of Attack	C_L/C_D	
	NACA 4412	NACA 6409
0	3.365	0.39
5	5.382	0.66

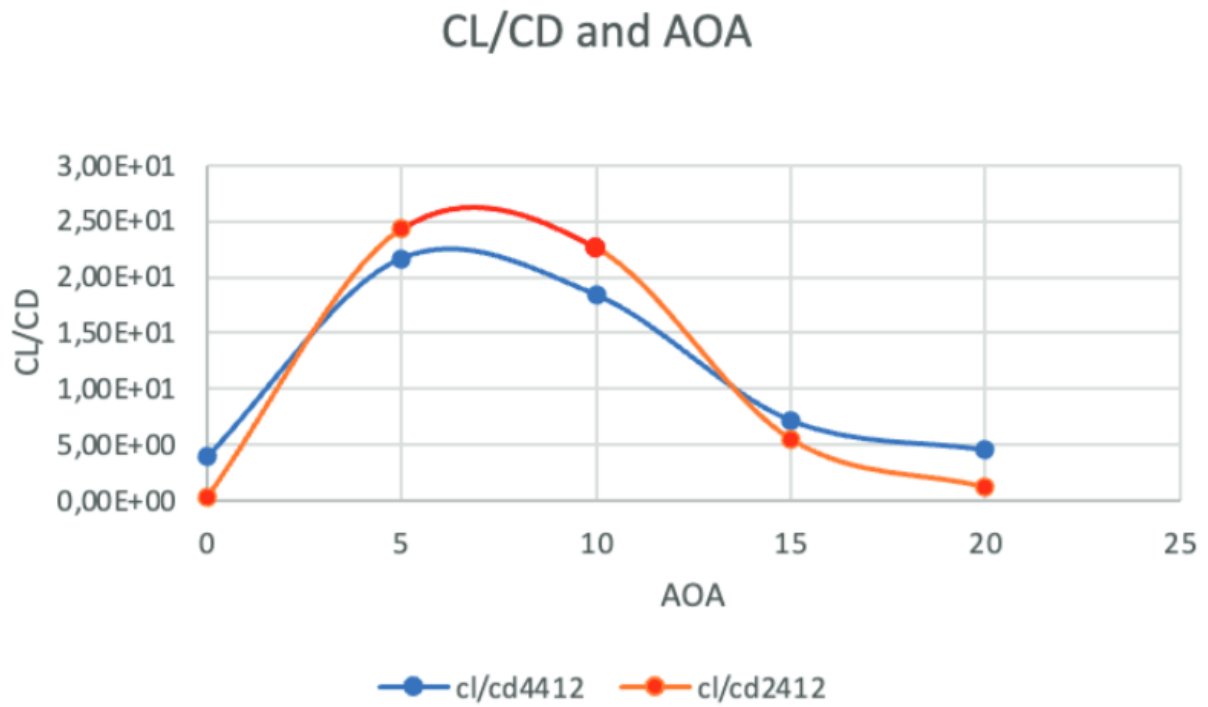


Figure 5 – Lift to Drag Coefficients and Angle of Attack NACA 2412 & NACA 4412 (Gok and Alnimer, 2024)

The power coefficient (C_p) is the fraction of available wind power converted to mechanical rotor power and is defined by the formula below.

$$C_p = \frac{P}{\frac{1}{2} \rho A v^3}$$

where:

- P = actual power extracted by the turbine
- ρ = air density (kg/m^3)
- A = swept area of the blades (m^2)
- v = wind speed (m/s)

(Xia et al, 2012)

Albert Betz defined the maximum power coefficient possible with a wind turbine as 0.593 and as stated by Dai et al, (2016) so far, no wind turbine has outperformed the Betz's Law. However, the latest technology can produce a C_p of 0.48 (Sohail and Farzaneh, 2022), this is shown in *Figure 6* that also shows the typical C_p curve.

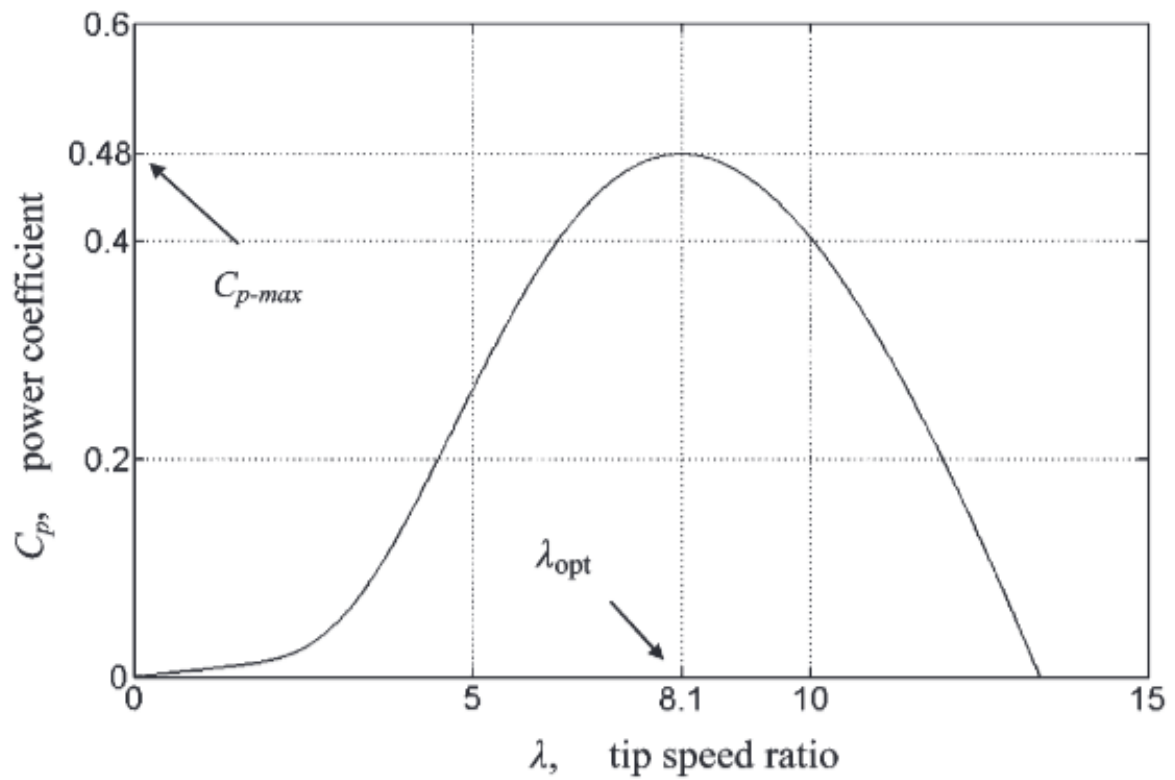


Figure 6 - Wind Turbine Blades Power Coefficient Curve. (Xia et al, 2012)

2.2 Optimal Dimensions and Blade Geometry

Table 2 provides specification details of a 60-kilowatt Vergnet GEV 15/60 wind turbine with a rotor diameter of 15 meters and *Table 3* provides technical specifications of a six-kilowatt wind turbine with a 7 meter rotor diameter.

Table 2 - Vergnet GEV 15/60 Data Sheet (wind-turbine-models.com, 2026)

Datasheet

Power

Rated power:	60.0 kW
Flexible power ratings:	-
Cut-in wind speed:	5.0 m/s
Rated wind speed:	15.0 m/s
Cut-out wind speed:	20.0 m/s
Survival wind speed:	60.0 m/s
Wind zone (DIBt):	-
Wind class (IEC):	-

Rotor

Diameter:	15.0 m
Swept area:	177.0 m ²

Table 3 - WE16K Wind Turbine Configuration Data (Wetzel et al, 2006)

Table General Configuration of the WE16K Wind Turbine		
	PDR	Kick-Off
General Configuration		
Rated Electrical Power (kW)	6	6
Rotation Axis	Horizontal	Horizontal
Rotor Diameter (m)	7	7
Number of Blades	3	3
Orientation	Upwind	Upwind
Power Regulation above Rated	Active Pitch to Feather	Active Pitch
Yaw Regulation	Active Yaw	Active Yaw
Speed Regulation	Fixed-Speed	Fixed-Speed
Generator Type	PM Synchronous	PM Synchronous
Hub Type	Rigid	Rigid
Hub Height (m)	30	30
Design Operating Environment & Performance		
IEC 61400-1 Wind Class	II-A	II-A
Rated Wind Speed (m/s)	9	9
Cut-in Wind Speed (m/s)	4.1	3.5
Cut-out Wind Speed (m/s)	25	25
Extreme Wind Speed (m/s)	60	60
Design Life (yrs)	20	20
Net Annual Energy Production		
NREL Reference Site (kWh)	21433	23755
IEC Class II-A Site (kWh)	28517	29373

Table 4, provided by Schubel and Crossley (2012) shows several different blade lengths currently in operation from one-megawatt output with a rotor diameter of fifty-seven meters up to seven-megawatt output with a 164-meter rotor diameter. This table provides a clear indication of expected blade length required for a specific output. At the bottom of *Table 4* a typical modern two megawatt turbine is detailed, with the rotor diameter at ninety meters with the blade length of forty-four meters,

swept area of 6362m² and made from pre-impregnated epoxy glass fibre and carbon fibre.

Table 4 - Wind Turbine Specifications (Schubel and Crossley, 2012)

Turbine name	Pitch or stall	Rotor dia (m)	No. of blades	Nacelle and rotor weight (kg)	Weight per swept area (kg/m ²)
Mitsubishi MWT-1000 (1 MW)	P	57	3	unspecified	
Nordex N90 (2.3 MW)	P	90	3	84500	13.3
Nordex N80 (2.5 MW)	P	80	3	80500	16
Repower 5 M (5 MW)	P	126	3	Unspecified	
Siemens SWT-3.6-107 (3.6 MW)	P	107	3	220000	24.5
Siemens SWT-2.3-93 (2.3 MW)	P	93	3	142000	20.9
Gamesa G90 - 2 MW (2 MW)	P	90	3	106000	16.7
Gamesa G58-850 (850 kW)	P	58	3	35000	13.3
Enercon E82 (2 MW)	P	82	3	Unspecified	
GE wind 3.6 sl (3.6 MW)	P	111	3	Unspecified	
Vestas V164 (7.0 MW)	P	164	3	Unspecified	
Vestas V90 (2 MW)	P	90	3	106000	16.7
Vestas V82 (1.65 MW)	P	82	3	95000	18

: A Typical modern 2 MW wind turbine specification

Rotor	
Diameter	90 m
Swept Area	6362 m ²
Rotational Speed	9 – 19 rpm
Direction of Rotation	Clockwise from front
Weight (including hub)	36 T
Top Head Weight	106 T
Blades	
Quantity	3
Length	44 m
Aerofoils	Delft University and FFA-W3
Material	Pre impregnated epoxy glass fibre + carbon fibre
Mass	5800 kg

Figure 7, 8, and Table 5 below show, how the blade geometry varies along the span with the taper profiling away from the root section. The root section is circular in profile and wider to provide a stable footing as shown in Figure 7, this allows a thicker and wider profile near the root to withstand higher bending moments, while the tip section can be a different profile and thinner to reduce drag.

- Root diameter of 5.8 m
- Maximum chord of 7.2 m
- Prebend of 7 m
- Uses the FFA-W3 airfoil family, including flatback airfoils for the root
- Airfoil polars computed using the incompressible 2D computational fluid dynamics solver EllipSys2D at representative Reynolds numbers

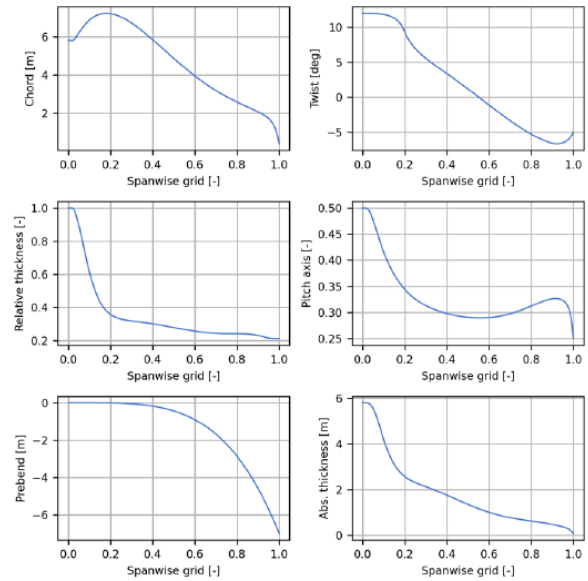
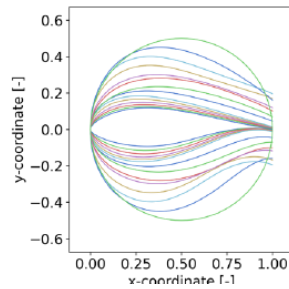


Figure 7 - IEA 22MW Wind turbine Blade Reference (National Renewable Energy Laboratory, 2024)

Thick-Airfoil Family for Large Blades

Tip-Region Airfoil



Primary Outboard Airfoil



Root Region Airfoil



Thin-Airfoil Family for Medium Blades

Tip-Region Airfoil



Primary Outboard Airfoil



Root Region Airfoil



Figure 8 - Aerofoil in families (U.S. Department of Energy, 2023)

Table 5 - DOWEC aerodynamic blade properties (Jonkman et al, 2009)

Node (-)	RNodes (m)	AeroTwst (°)	DRNodes (m)	Chord (m)	Airfoil Table (-)
1	2.8667	13.308	2.7333	3.542	Cylinder1.dat
2	5.6000	13.308	2.7333	3.854	Cylinder1.dat
3	8.3333	13.308	2.7333	4.167	Cylinder2.dat
4	11.7500	13.308	4.1000	4.557	DU40_A17.dat
5	15.8500	11.480	4.1000	4.652	DU35_A17.dat
6	19.9500	10.162	4.1000	4.458	DU35_A17.dat
7	24.0500	9.011	4.1000	4.249	DU30_A17.dat
8	28.1500	7.795	4.1000	4.007	DU25_A17.dat
9	32.2500	6.544	4.1000	3.748	DU25_A17.dat
10	36.3500	5.361	4.1000	3.502	DU21_A17.dat
11	40.4500	4.188	4.1000	3.256	DU21_A17.dat
12	44.5500	3.125	4.1000	3.010	NACA64_A17.dat
13	48.6500	2.319	4.1000	2.764	NACA64_A17.dat
14	52.7500	1.526	4.1000	2.518	NACA64_A17.dat
15	56.1667	0.863	2.7333	2.313	NACA64_A17.dat
16	58.9000	0.370	2.7333	2.086	NACA64_A17.dat
17	61.6333	0.106	2.7333	1.419	NACA64_A17.dat

Tip Speed Ratio (TSR) is important when optimizing the efficiency of the rotor and the generator. Hosseini et al, (2022) indicate this by stating blade sets that spin too slowly will allow wind to pass without harvesting its energy, while blades that spin too fast will be travelling in the previous blade turbulent wake. Research indicates that three-bladed horizontal turbines typically operates most efficiently within the TSR range of 6 to 8 (Business Norway, 2025). Using the tip speed ratio equation, the TSR of current wind turbines were calculated and are shown below.

$$\lambda = \frac{\Omega_r}{v_\omega}$$

where:

λ = Tip Speed Ratio

Ω = Rotational Velocity

r = Radius

v_ω = Windspeed

GE 3 MW TSR = 7-8

2.3 Material Properties

Three categories of material were researched with Figure 9, 10 and 11 providing graphical evidence of the materials fatigue resistance, strength, density, fracture toughness and Vickers Hardness.

Metals

Metals provide high strength, fatigue resistance, and good manufacturability. However, metals have a high density, which increases gravitational loading, reducing efficiency and additional wear on bearings (Xu et al, 2025).

Ceramics

Technical ceramics such as silicon carbide provide high hardness and thermal resistance. Despite these advantages ceramics are brittle and susceptible to catastrophic fracture under impact or cyclic loading (Fan et al, 2024).

Composites

Song et al (2019) states, carbon fibre reinforced polymer (CFRP) and glass fibre reinforced polymer (GFRP) composites combine high specific strength, low density and good fatigue resistance, although recycling remains difficult and the material is costly.

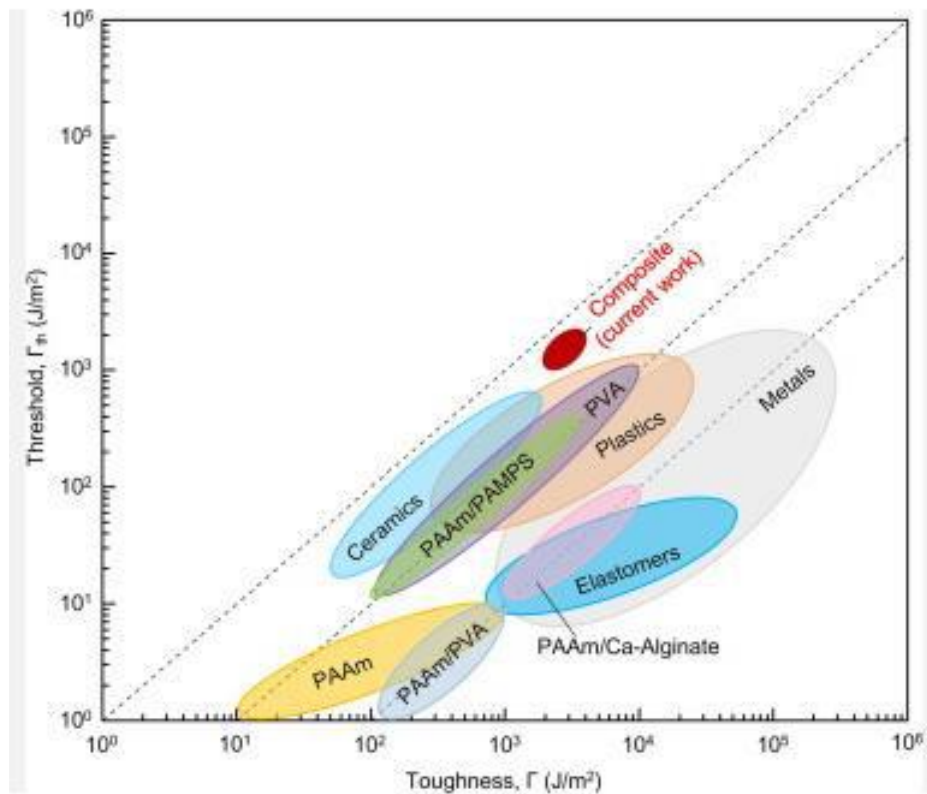


Figure 9 - Fatigue-Resistance of Material (2020, Materials Today)

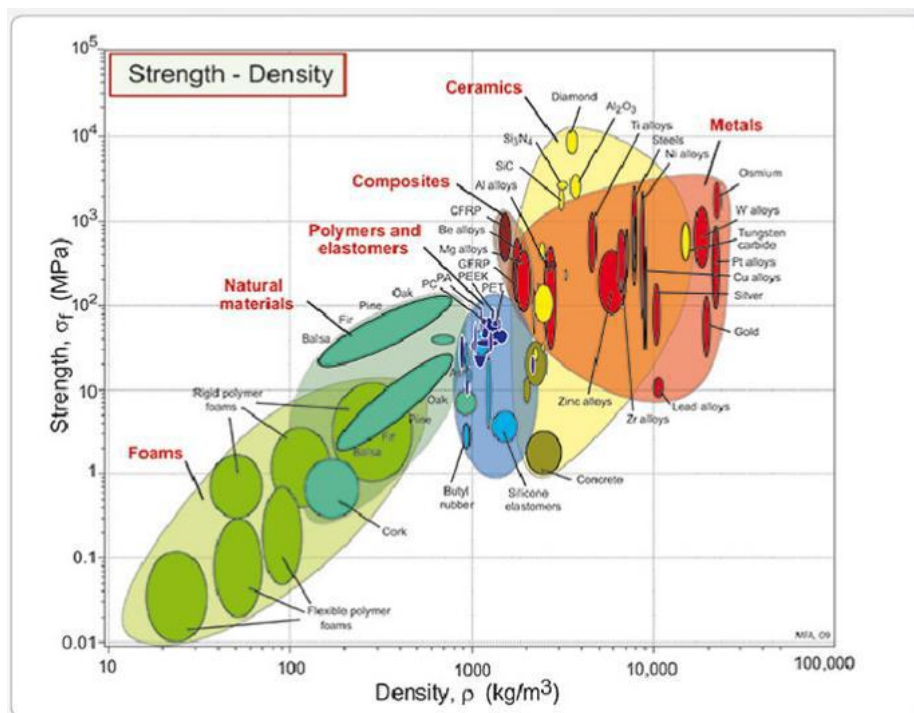


Figure 10 - Granta chart of Strength & Density (2025, The Open University)

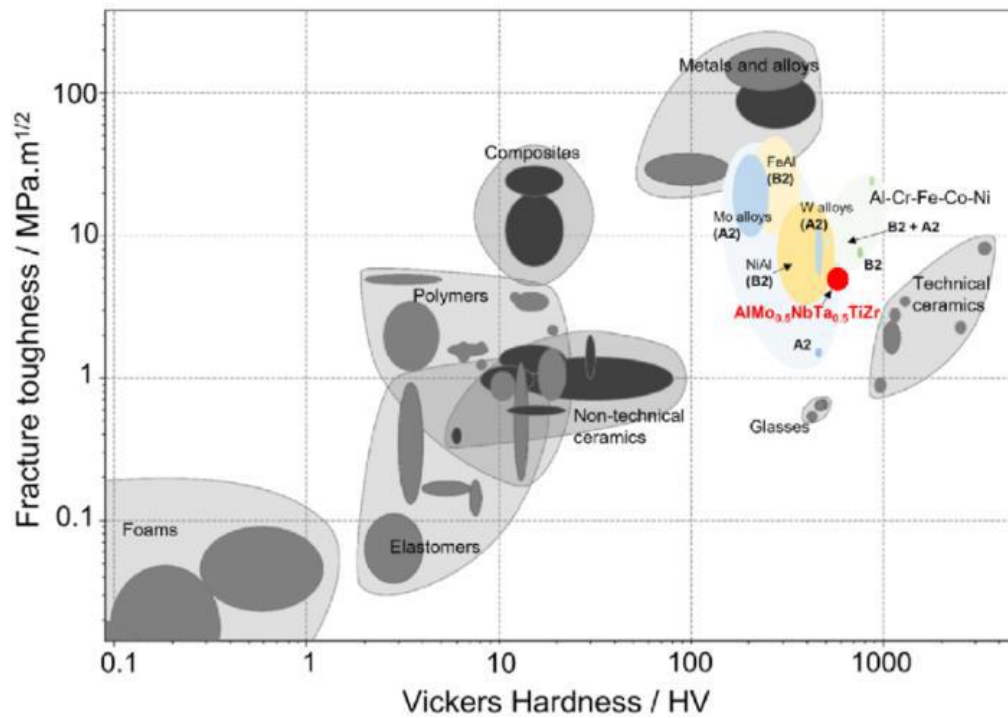


Figure 51 - Fracture Toughness & Vickers Hardness Chart (2025, ResearchGate)

Figure 12 shows the cost of each material.

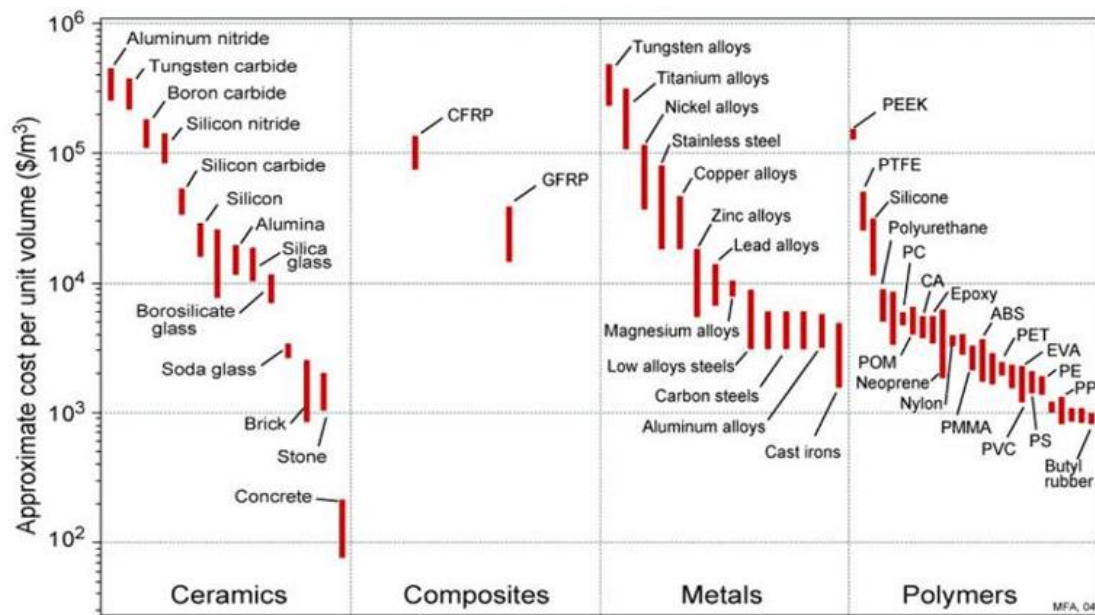


Figure 62- Graph of Material Cost (2025, Proxom)

These comparisons favour the composites for blade construction due to their high specific strength and fatigue resistance with reduced structural mass, whereas metals incur a weight penalty and ceramics remain limited by low fracture toughness.

2.4 Environmental Factors

Wind turbine blades as shown by Tavner et al, (2013) experience variable environmental conditions as shown in *Figure 13*. From sub-zero temperatures to above 40°C, causing thermal dimensional changes, icing and UV degradation. Gusts, turbulence and wind shear create fluctuating aerodynamic loads that drive fatigue, while rain, moisture and lightning create additional environmental loading, with marine and coastal environments enhancing salt-induced corrosion and erosion.

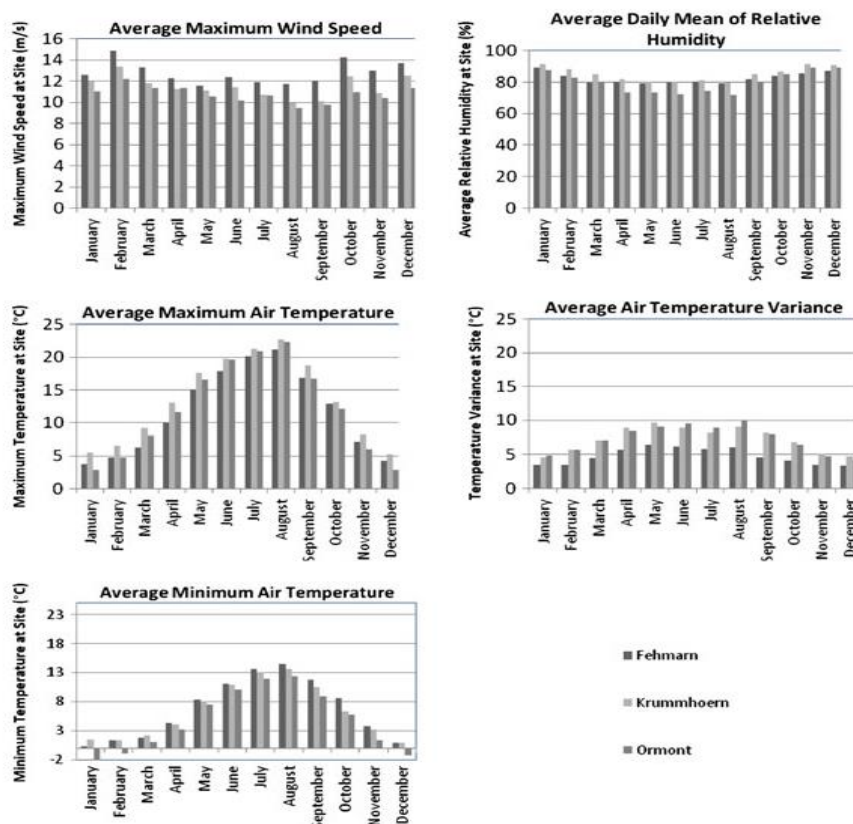


Figure 13 – Study of Weather and Location Effects (Tavner et al, 2013)

3 Design Specifications

Pentrehafod School in Swansea is looking for a renewable energy source to go net zero on energy usage. The school requires a wind turbine to produce approximately 60,752 kWh/year, providing enough energy to electrify the heating system. The price needs to be competitive with competing renewable energy sources as provided by Solar Powered Schools (2026). *Table 6* provides the specification of the customer and engineering requirements.

Table 6 - Specification Table

Performance	• Produce 60,752kWh/Year of electricity or more • Minimum Power 6935.16W • Efficiency (C_p) of 0.4 • TSR (λ) = 7 • Lift Coefficient (C_l) = 1.0
Environment	• Coastal Weather (Corrosive and high wind gusts) • Average wind speed 6 m/s • Air density of approximately 1.255 kg/m³ • Temperatures range between -20°C and 40°C
Maintenance	• Annual Inspection and service • 1 day of down time for Annual Inspection and Service
Target Product Cost	• £66,000 per turbine
Quantity	• Thousand units (Only 1 wind turbine for the school)
Size	• Blade radius less than 10 meter
Manufacturing Facilities	• Design for ease of production at a scale of a thousand units
Materials	• Lightweight • Corrosion Resistance • Fatigue resistance • Wear resistance • UV resistance • High stiffness
Aesthetic/Finish	• Low visual impact on the surrounding • Finish resistance to fading and discoloration • No sharp edges
Product Life Span	• 25 years
Installation	• Must be able to be assembled with a 50-tonne crane • Be assembled on site
Health & Safety	• Integrated lightning protection system • Noise level to a minimum • Fire resistance electrical enclosures. • Remote monitoring for fault detection, automated braking and safety shut down

3.1 Blade Geometry

Based on the aerodynamic comparison in Section 2.1, NACA 2412 was selected because its favourable lift-to-drag performance over a wider angle of attack range provides greater tolerance to the variable operating conditions.

The calculations were carried out using the data specified in *Table 6* and the formulas supplied by University of Wales Trinity Saint David (UWTSD).

3.1.1 Blade Length

The final radius design length of a blade is 6.5 meters from the minimum requirement of 6.38 meters, allowing a potential 3.8% increase in electricity production over the minimum requirement. The calculation used to determine the minimum blade length is shown below.

$$P = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \cdot c_P$$

$$P = 6935.16 \text{ W}$$

$$\rho = 1.255 \text{ kg/m}^3$$

$$A = \text{Area (m}^2\text{)}$$

$$v = 6 \text{ m/s}$$

$$c_P = 0.4$$

Rearrange to solve A:

$$A = \frac{2P}{\rho v^3 c_P}$$

$$A = \frac{2 \cdot 6935.16}{1.255 \cdot 6^3 \cdot 0.4}$$

$$A = 127.92\text{m}^2$$

Finding the minimum blade length:

$$R = \sqrt{\frac{A}{\pi}}$$

$$R = \sqrt{\frac{127.92}{\pi}}$$

$$R = 6.38\text{m}$$

The blade length at 6.5 meters, provides a swept area of 132.73m² and a power output of 7196.21 watts, increasing the blade length to seven meters would add unnecessary material and manufacturing cost.

3.1.2 Chord Lengths

The chord lengths were calculated using the formula below and the blade was divided into five sections. Results are shown in *Table 7*.

$$c(r) = \frac{8\pi R}{N \cdot C_l \cdot \lambda} \cdot \frac{\left(1 - \frac{r}{R}\right)}{r}$$

$$R = 6.5\text{m}$$

$$\lambda = 7$$

$$\text{Number of Blades } (N) = 3$$

$$C_l = 1.0$$

$$\text{Radial Positions } \frac{r}{R} = 0.2, 0.4, 0.6, 0.8, 1.0$$

$$\begin{aligned} \text{Distance from the hub to the radial position where } c(r) \text{ is being calculated } r \\ = 1.3, 2.6, 3.9, 5.2, 6.5\text{m} \end{aligned}$$

Table 7 - Chord Length Calculation Results

r/R	r (m)	Chord Length (m)
0.2	1.3	0.918
0.4	2.6	0.567
0.6	3.9	0.396
0.8	5.2	0.302
1	6.5	0

The calculated tip chord was adjusted from 0 m to 0.243 m to improve CAD loft continuity and manufacturability while retaining the intended spanwise taper . This can be seen in *Table 8*. The calculation for the camber line and the upper and lower blade thickness from the camber line was carried out using *Table 8*, results can be seen below as plotted graphs providing a 2D image of each sections profile. Result table can be seen in Appendix B.

Table 8 - Chord Length Calculations

r/R	r (m)	Chord Length (m)
0.2	1.3	0.918
0.4	2.6	0.567
0.6	3.9	0.396
0.8	5.2	0.302
1	6.5	0.243

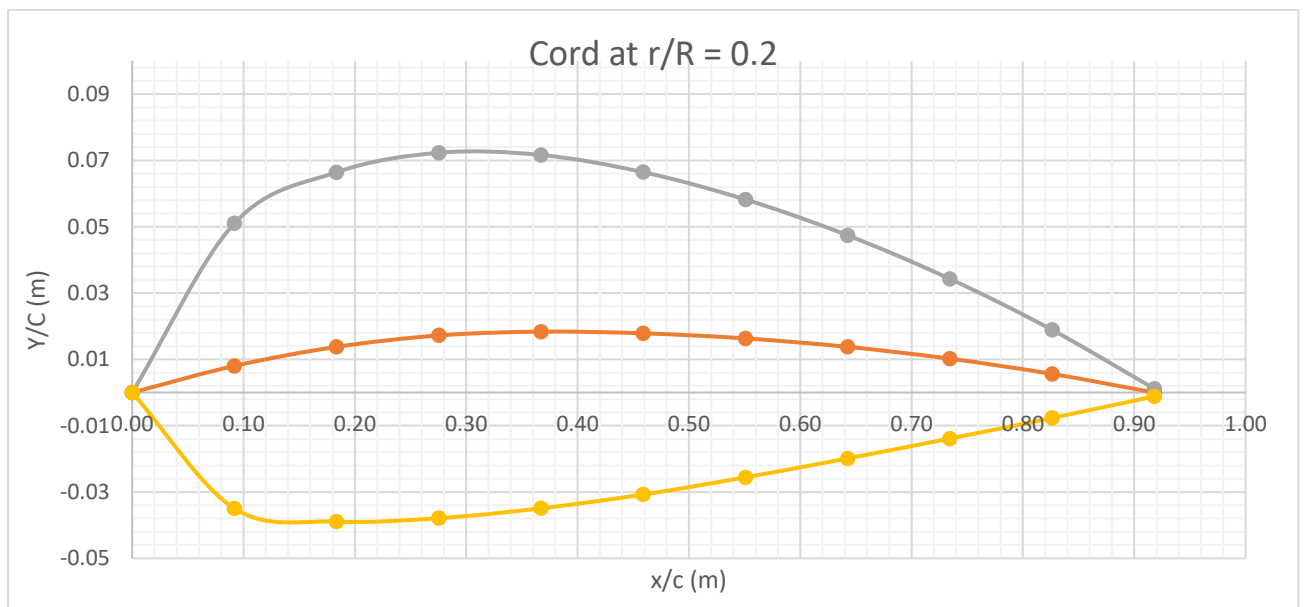


Figure 74 - 0.2 r/R Aerofoil Profile

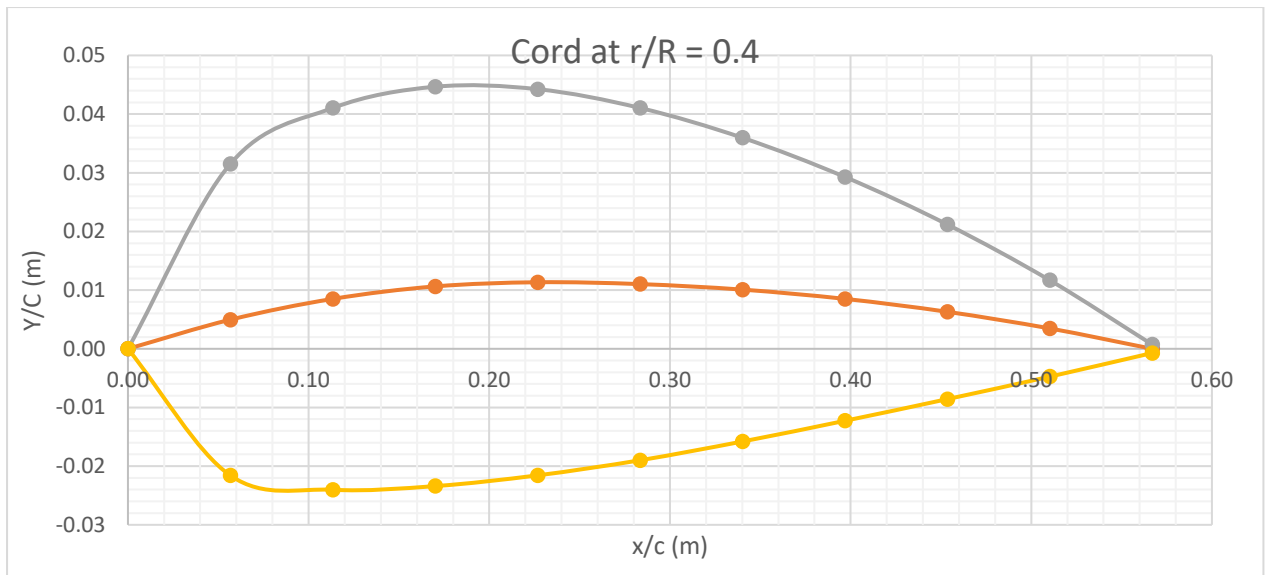


Figure 85 - 0.4 r/R Aerofoil Profile

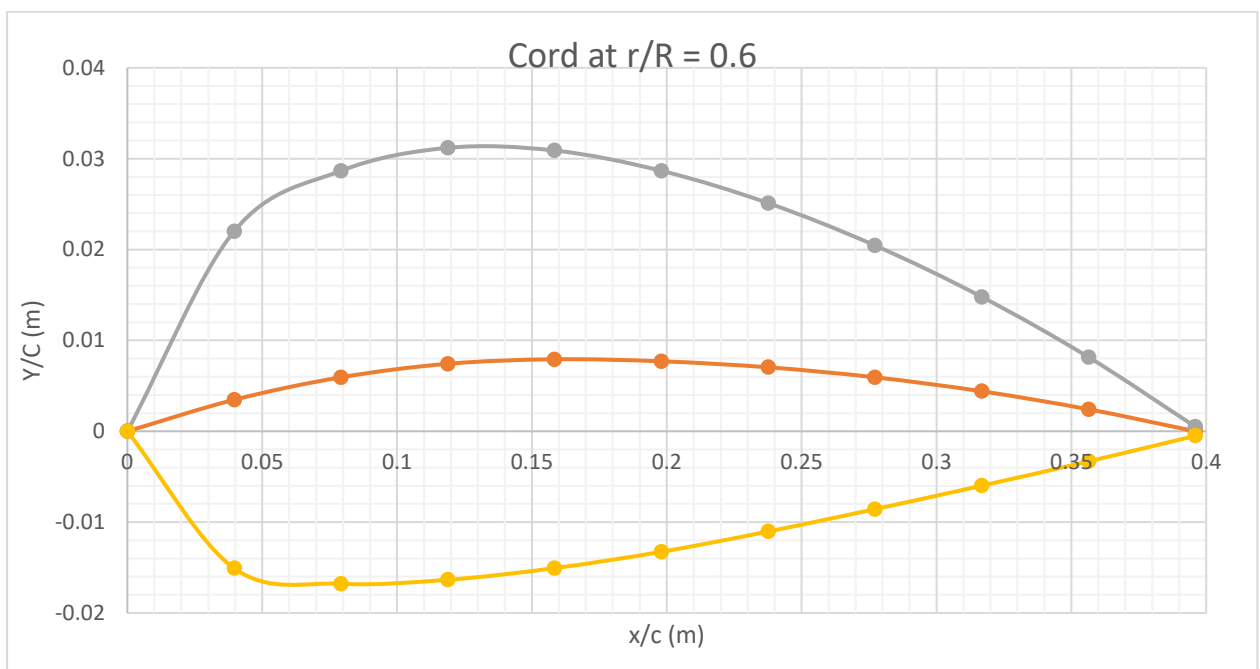


Figure 96 - 0.6 r/R Aerofoil Profile

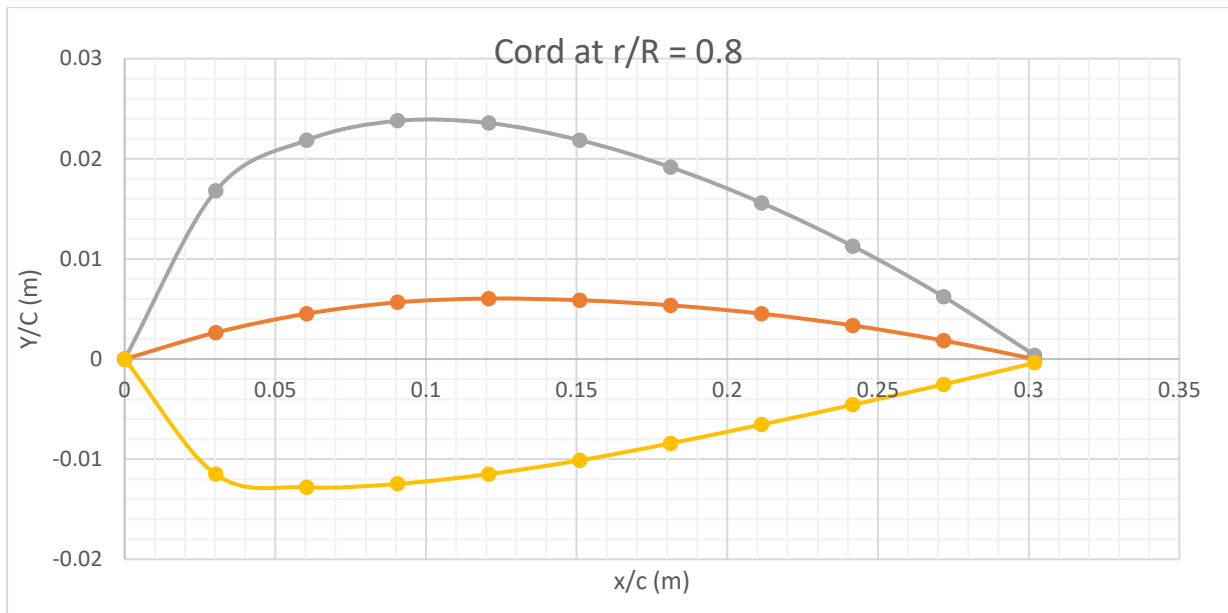


Figure 107 - 0.8 r/R Aerofoil Profile

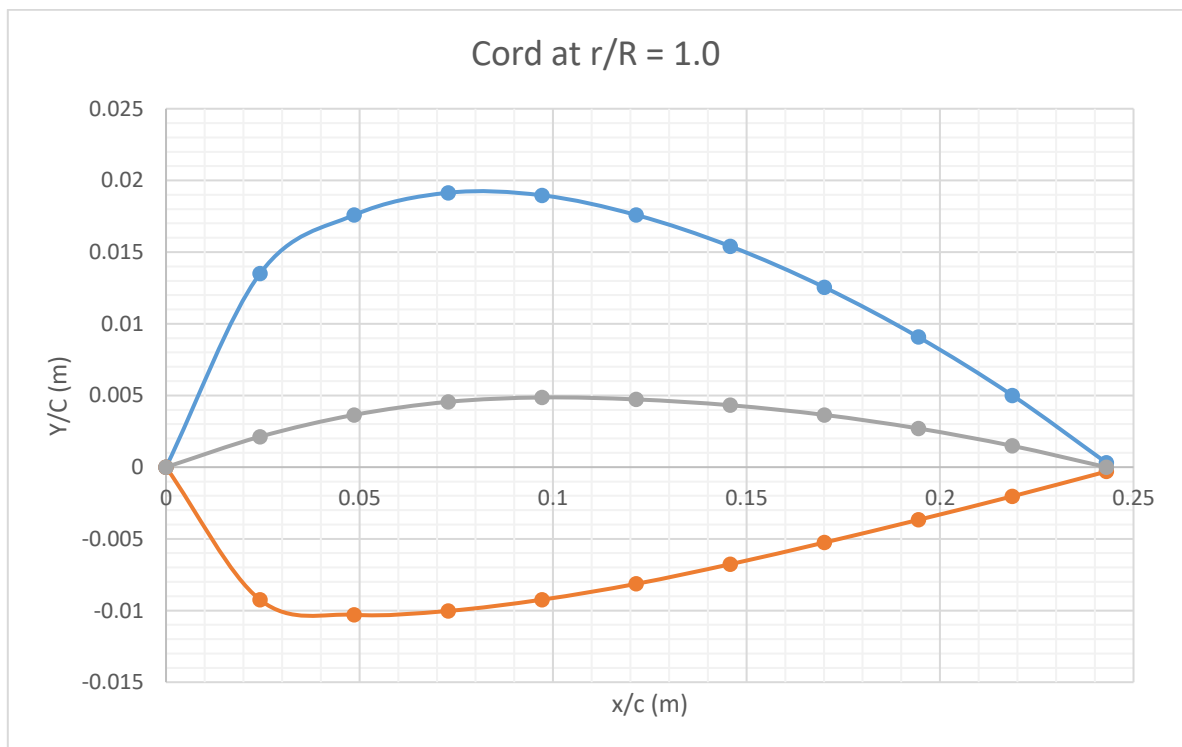


Figure 118 - 1.0 r/R Aerofoil Profile

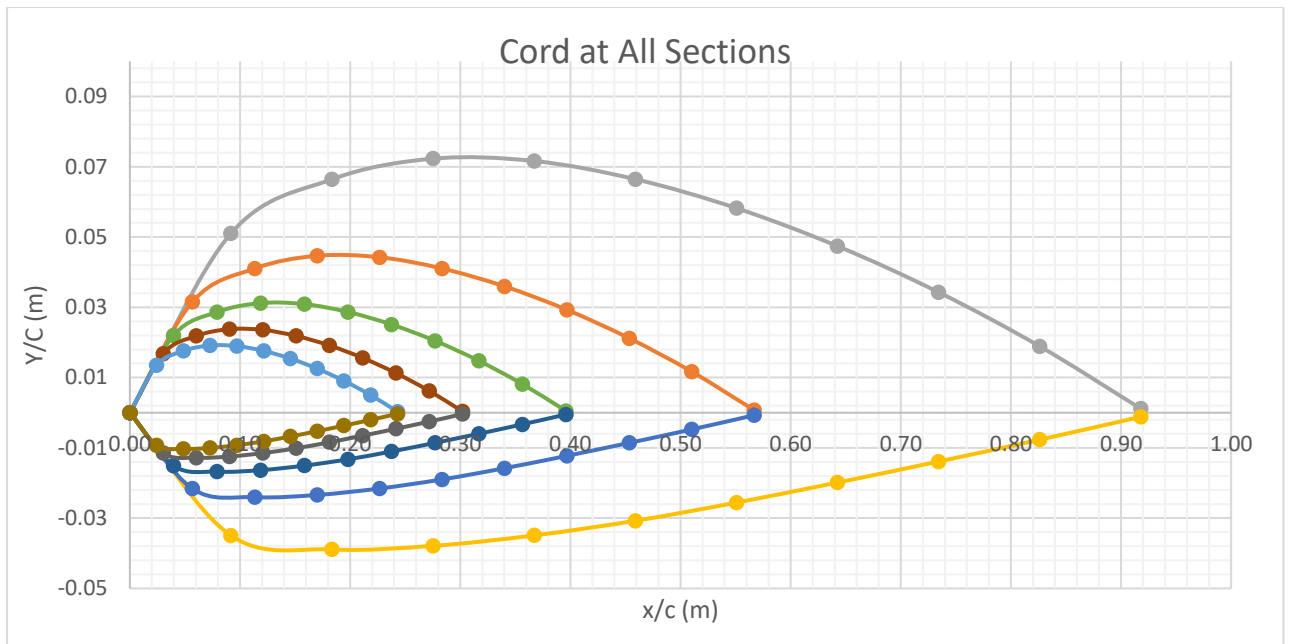


Figure 19 - Profile of All Section

4 Material Selection

4.1 Weighted Decision Matrix

Weighted decision matrix *Table 9* was used to compare materials and rank candidate materials against the design requirements. Property data obtained from ANSYS (2026) and supporting literature with an in-depth data *Table 23* provided in Appendix C. The material weighting factors calculations have been carried out as provided by the UWTSD.

Table 9 - Material Weighted Decision Matrix

Material	Density	Tensile	Fracture Toughness	Fatigue Strength	CO2 footprint	Recyclability	Price	Manufacturability	
Scaled Strength	0.15	0.2	0.15	0.2	0.05	0.1	0.1	0.05	Final Score
Aluminium 6061	57.90	18.9	36.50	12.00	22.70	100.00	100.00	100.00	43.8
Structural Steel	20.00	29.8	100.00	21.30	100.00	100.00	81.40	100.00	67
Silicon Carbide	49.80	24.4	3.60	34.80	29.20	66.70	14.80	50.00	35.9
Zirconia	25.70	8	1.90	11.50	48.30	66.70	5.90	50.00	20.7
GFRP	96.30	15.2	15.00	10.00	30.50	66.70	89.00	75.00	43.5
CFRP	100.00	100.00	73.90	100.00	4.10	33.30	25.10	75.00	81.4

4.2 Materials Recommendation

CFRP achieved the highest overall score due to its excellent fatigue resistance, low density, and high strength. Although the initial cost is higher than the alternative materials, the reduced maintenance requirements and longevity of the blade life justify its selection. GFRP also demonstrated robust performance and could be an alternative, while metals retain an advantage in recyclability.

5 Exploration of Manufacturing Routes

5.1 Metals

5.1.1 Casting

Casting is a manufacturing process where molten metal is poured into the desired shape cavity mould and allowed to solidify into the desired shape. There are two types of casting, expandable mould casting such as sand casting and permanent mould casting such as die casting (UWTSD, 2026).

Advantages

Casting brings a variety of advantages as this process can be used to manufacture complex shapes with high dimensional accuracy, ensuring high structural integrity. Casting can be used for large parts and almost all metals, this process is seen as cost-effective in mass production (UWTSD, 2026).

Limitations

The limitation of casting is the risk of shrinkage, porosity, cracks, and uneven cooling all affecting the quality and strength of the product. Casting requires precise temperature and flow control and uses vast amounts of energy. Finishing quality of casting often requires machining to produce smooth faces (UWTSD, 2026).

5.1.2 Extrusion

Extrusion is a process where a metal billet is forced through a shaped die to produce a product with a constant cross-section. There are two main types of extrusion, direct and indirect (Suwanpreecha and Manonukul, 2022).

Advantages

Extrusion is ideal for producing uniformed cross-sectional products at high production rates, the process produces a good grain structure and strength while ensuring a quality surface finish. This process also has an exceptionally low material waste and can be used for many metals (Mechanical Funda, 2020).

Limitations

Limitations of extrusion are that only constant cross-section products can be produced, it requires expensive tooling, setup time, and the die wear leads to maintenance cost and downtime.

5.2 Ceramics

There are several different manufacturing processes for ceramics, but for advanced ceramic components. Additive manufacturing (AM) builds components layer by layer from ceramic powders, slurries or filaments which then can use the sintering process. Sintering is a thermal densification process where compacted ceramic particles bond together when heated below their melting temperature as shown in *Figure 20* (Kintek Solutions, 2026).

Advantages

AM allows manufacturing of complex geometries, lattice structures that increases strength while ensuring the lightest possible weight. The process allows bespoke components to be manufactured without the need to source or produce moulds or dies and it does not produce vast amount of material waste and machining. Sintering

improves microstructure that improves the products hardness, wear resistance, density and strength (Dadkhah et al, 2023).

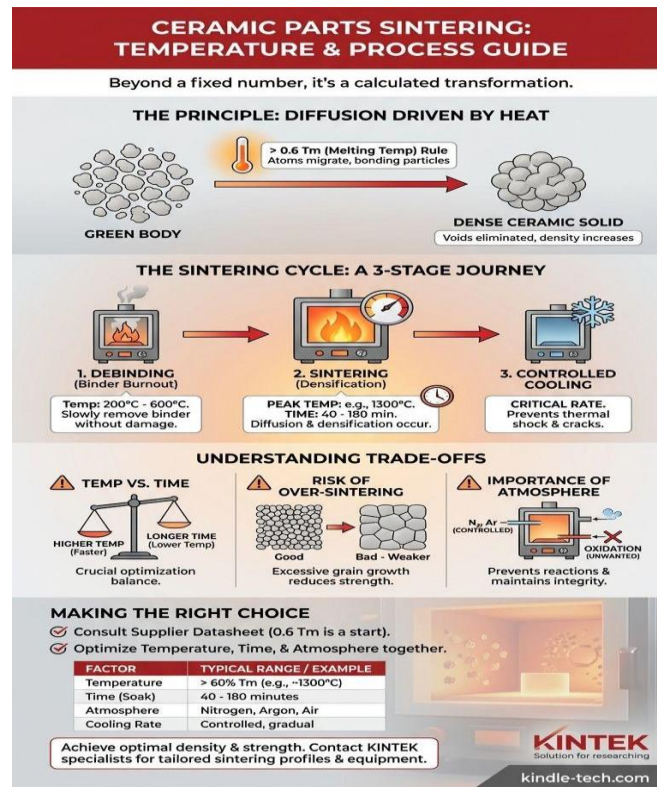


Figure 120 - Sintering Process (Kintek Solution, 2026)

Limitations

AM equipment has a high purchase and maintenance costs; the production rate is slow compared to conventional mass production methods and the finish quality is poor (Dadkhah et al, 2023). Sintering uses a lot of energy and can cause warping, cracking, or deformation. This process can also take hours with shrinkage also an issue. Ceramic manufacturing suffers with their brittleness challenges, they are susceptible to thermal shock, develop common defects such as porosity, inclusions and have poor impact resistance which make them vulnerable when impacts, shock loading or sudden mechanical forces are experienced during the manufacturing or handling processes (Murenzi et al, 2025).

5.3 Polymer Composites

Vacuum infusion *Figure 21* is a polymer composite manufacturing technique where resin is drawn into a dry fibre layup under vacuum, producing a strong, lightweight composite laminate (Fibre Glast Development Corporation, 2003).

Vacuum infusion process, simulation and testing

- Vacuum infusion process
- Infusion trials on flat or curved geometries of specific areas

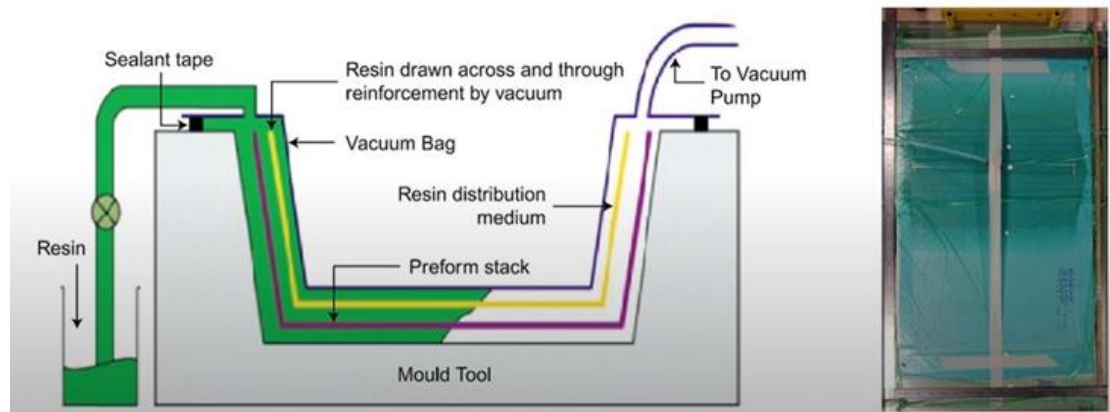


Figure 131 - Composite Manufacturing Process (2023, DTU Wind and Energy Systems)

Advantages

Vacuum infusion tooling costs are lower than resin transfer moulding, while providing high fibre volume fractions, low void content, and an improved wet-out and laminate quality with high consistency. Vacuum infusion is ideal for large structures such as wind turbine blades while also reducing the workers exposure to resin emissions (Campell, 2004).

Limitations

Vacuum infusion has a long curing time as shown in *Figure 22*. The process is also sensitive to permeability variations and vacuum leaks can severely affect laminate quality, causing dry spots from incomplete resin flow (Campell, 2004).

Curing process and process temperatures

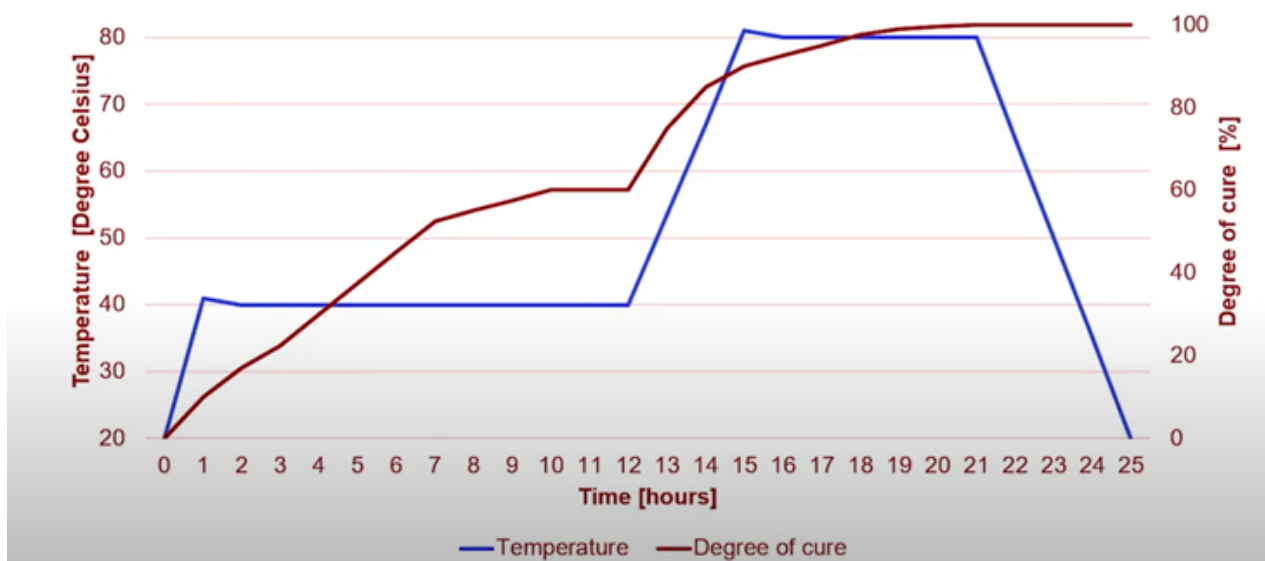


Figure 142 - Composites Curing Time (2023, DTU Wind and Energy Systems)

5.4 Comparative Manufacturing Analysis

Table 10 compares selected manufacturing routes based on production cost, scalability, and manufacturing time.

Table 10 – Analysis of Manufacturing Processes (Kalpakjian and Schmid, 2018)

Manufacturing Process	Production Cost	Scalability	Manufacturing Time
Metal Casting	Low tooling cost for sand but high tooling cost for die casting and permanent moulds initial tooling cost, but low unit cost for high-volume production.	Excellent scalability for mass production.	Moderate. Production cycles are fast although cooling and post-machining increase total manufacturing time.
Metal Extrusion	High tooling costs but low material waste and unit cost at large production volumes.	Excellent scalability due to continuous production capability.	Fast production rate once the die/extrusion process is established.
Ceramics Additive Manufacturing & Sintering	Very high equipment and operating costs, with the additional energy cost also associated with sintering.	Limited scalability due to slow manufacturing time, more suitable for customized production.	Long manufacturing times due to the layered build up of the product and the sintering cycles can take several hours.
Polymer Composites Vacuum Infusion	Moderate tooling cost.	Good scalability for large structure such as wind turbine blades. Production capacity is limited by curing time.	Long production cycles due to resin infusion and curing times taking just over a day.

With Health and Safety along with environmental issues increasing as an importance in manufacturing process and material decision, *Table 11* shows these factors for each process.

Table 11 - Environmental Impacts and Safety Hazards (Health and Safety Executive, 2026)

Manufacturing Process	Environmental Impact	Safety Hazards
Metal Casting	High energy use, emissions, wastage e.g. sprue, gating system and sand. Recyclable materials.	Burns, molten metal splashes, fumes, explosions.
Metal Extrusion	Moderate energy use, low waste.	Crushing, entanglement, burns, high pressure, hot surfaces.
Ceramic Additive Manufacturing and Sintering	Low waste, high electrical consumption	Dust inhalations, furnace burn, airborne particles.
Polymer Composites Vacuum Infusion	Low energy use, reduced volatile organic compounds. Recycling challenges.	resin exposure, skin irritation, respiratory hazards.

Tables 10 and 11 indicate vacuum infusion provides the best overall manufacturing route as it combines scalable large parts manufacturing with moderate tooling and lower process temperatures. Its principal disadvantages remain cure time, resin and fibre hazards and poor composite recyclability.

6 Cost Evaluation

6.1 Raw Material Cost

With the CAD providing a total volume of 0.06643m^3 , when the blade was hollowed out to include only a ten-millimetre thickness this represents five millimetres thickness of material at each end of the sandwich core. Using the cost findings from ANSYS (2026) *Table 12* provides the raw material cost for one blade and the set of three.

Table 12 - Raw Material Cost

Material	Price £/m ³	Per Blade (£)	Set of Three (£)
Aluminium 6061	6,210.00	412.53	1,237.59
Structural Steel	7,630.00	506.86	1,520.58
Silicon Carbide	41,950.00	2,786.74	8,360.22
Zirconia	105,000.00	6,975.15	20,925.45
GFRP	6,975.00	463.35	1,390.05
CFRP	24,700.00	1,640.82	4,922.46

Table 12 demonstrates the substantial influence of material selection on blade cost. Although CFRP produces the third highest cost, its high valued properties such as

strength and fatigue performance result in the highest WDM score. GFRP provides a lower cost composite alternative, demonstrating the trade-off between initial material expenditure and mechanical performance.

6.2 Manufacturing Costs

Schubel, (2010) indicates that a vacuum infusion manufacturing cost are 51% materials, 41% labour which means that the other 8% is for maintenance, tooling, defects, and other costs. Using the information from the previous sections and summaries in *Table 10*, we can estimate the costs of the other manufacturing processes. This is shown in *Table 13* which also provides the overall cost of each manufacturing process.

Table 13 - Manufacturing Costs

Material	Material Cost Per Blade (£)	Process Cost Material %	Process Cost Labour %	Process Cost Other %	Manufacturing Cost per Blade (£)	Manufacturing Cost Per Set of 3 (£)
Aluminium 6061	412.53	57.00	28	15	723.74	2171.22
Structural Steel	506.86	57.00	28	15	889.23	2667.69
Silicon Carbide	2,786.74	33.33	33.33	33.33	8361.06	25083.18
Zirconia	6,975.15	33.33	33.33	33.33	20,927.54	62782.62
GFRP	463.35	51.00	41.00	8	908.53	2725.59
CFRP	1,640.82	51.00	41.00	8	3217.3	9651.9

Table 13 shows that the metal and GFRP blades would be a third of the price of CFRP. CFRP selection is based on its overall performance rather than minimum initial cost as shown in the WDM, *Table 9*.

7 Mechanical Properties Analysis

7.1 Aerodynamics Force Calculations

The calculations for the blade designs lift and drag forces are calculated at each section point using formulas provided by UWTSD, the results are provided in *Table 14*. Using data provided by Guerrero et al, (2023) when lift coefficient is 1.0012, drag coefficient is 0.00978 and with blades maximum operating wind speed of 25 m/s and the maximum recorded wind speed in the area, 48 m/s.

Table 14 - Lift and Drag Force Per Section

r/R	Area (m ²)	25m/s wind speed		Max wind (48m/s)	
		Lift (N)	Drag (N)	Lift (N)	Drag (N)
0-0.2	1.758	673.85	6.582333798	2484.07295	24.27
0.2 - 0.4	1.963	752.32	7.3488387	2773.340276	27.09
0.4-0.6	1.276	489.09	4.777595022	1802.991906	17.61
0.6-0.8	0.925	354.46	3.462458098	1306.679176	12.76
0.8-1	0.722	276.8	2.703879045	1020.402946	9.97

7.2 Stress Analysis

7.2.1 Bending Stress

For a cantilevered item such as the wind blade the highest bending stress will occur near the root, by multiplying each sectional force by its midpoint distance and adding the total up provides the bending moment which is 6.73 kNm at 25 m/s windspeed

and 24.8 kNm at 48 m/s. With the information from the SolidWorks design the bending stress is calculated using the equation below.

$$\sigma = \frac{My}{I}$$

σ = Bending Stress

M = Bending Moment

y = 150 mm *(From a solid blade)

I = 397,443,569.54 mm⁴ *(From a solid blade)

$$\sigma = \frac{6726640 \cdot 150}{397,433,569.54} = 2.54 \text{ N/mm}^2 (\text{MPa})$$

Therefore, the root bending stress at 25 m/s wind speed using 300mm solid diameter CAD is 2.54 N/mm². The bending stress at 48 m/s is 9.36 N/mm² as shown in the calculation below.

$$\sigma = \frac{24800000 \cdot 150}{397,433,569.54} = 9.36 \text{ N/mm}^2 (\text{MPa})$$

7.2.2 Torsional Stress

Torsional stress was calculated using the formula below using only the first two parts.

Torque was calculated by calculating the coefficient mean of area over length and then applied to the aerodynamic torque formula, these solutions can be found in Appendix D. T at 25 m/s is 126.85 Nm and at 48 m/s is 467.6 Nm

$$\frac{T}{J} = \frac{\tau}{r} = \frac{G\theta}{L}$$

$$\tau = \frac{Tr}{J}$$

τ = Shear Stress

$T = 126850 \text{ N/mm}$ at 25 m/s or 467600 N/mm at 48 m/s

$r = 150\text{mm}$ * Solid CAD design

$J = 795,076,259 \text{ mm}^4$ * Retrieved from solid CAD design

Shear stress for 25 m/s windspeed

$$\tau = \frac{126850 \cdot 150}{795076259} = 0.024 \text{ N/mm}^2 \text{ (MPa)}$$

Shear stress for 48 m/s windspeed

$$\tau = \frac{467600 \cdot 150}{795076259} = 0.088 \text{ N/mm}^2 \text{ (MPa)}$$

7.3 Stress Comparison and Safety Factor

Table 15 shows the materials tensile strength and fatigue strength against the calculated maximum bending stress of 9.36 MPa and provides a factor of safety for both properties.

Table 15 - Tensile and Fatigue Factors of Safety

Material	Max Bending Stress (MPa)	Yield (MPa)	Static Strength Factor of Safety	Fatigue Strength at 10^7 cycles (MPa)	Fatigue Strength Factor of Safety
Aluminium 6061	9.36	260	27.78	121.5	12.98
Structural Steel	9.36	275	29.38	215.5	23.02
Silicon Carbide	9.36	405	43.27	351	37.50
Zirconia	9.36	132.5	14.16	116	12.39
GFRP	9.36	251.5	26.87	100.8	10.77
CFRP	9.36	1,660.00	177.35	1,007.50	107.64

Table 16 provides the factor of safety of torsion stress against each material. Shear strength data was used for metallic and flexural strength for the other materials.

Table 16 - Shear and Flexural Factor of Safety

Material	Max Bending Stress (MPa)	Shear Strength or Flexural Strength (MPa)	Shear Strength Factor of Safety
Aluminium 6061	9.36	201.50	21.53
Structural Steel	9.36	366.00	39.10
Silicon Carbide	9.36	480.00	51.28
Zirconia	9.36	186.00	19.87
GFRP	9.36	264.50	28.26
CFRP	9.36	467.00	49.89

The mechanical analysis identified at the extreme wind conditions of 48 m/s produces a maximum root bending stress of 9.36 MPa and a torsional stress of 0.088MPa. The material comparison demonstrates that the calculated stresses remain substantially below the applicable material strength limits. CFRP provides the greatest strength and fatigue safety factor, reinforcing its selection. However, these results are comparative, based on the solid CAD blade geometry providing higher factor of safety, a final hollow CFRP blade would require further structural validation using FEA.

8 Comparative Analysis

Table 17 integrates the material, manufacturing and structural analysis. CFRP offers the highest overall blade suitability because its strength, fatigue performance and calculated safety margins offset its higher cost and limited recyclability. Vacuum infusion is compatible with large CFRP structures, although cure time, void formation and end of life processing remain limitations.

Table 17 – Comparative Analysis

Criterion	Metals	Ceramics	GFRP	CFRP
Mechanical Performance	High strength, but heavy	High Stiffness, but brittle	Good strength to weight ratio	Highest strength to weight ratio and fatigue performance
Blade Mass	High	High/Moderate	Low	Lowest
Manufacturing Sustainability	Moderate	Poor for large blades	High	High
Scalability	Moderate	Poor	High	High
Defect Concerns	Porosity, cracking	Cracking, porosity	Voids, dry spots	Voids, dry spots
Cost	Moderate	High	Low cost composite	High
Recyclability	Good	Moderate	Poor	Poor
Overall, Blade Suitability	Moderate	Low	High	Highest

9 Blade Drawing

Figures 24 to 27 present the final 6.5 m NACA 2412 CAD model, spanwise section locations and manufacturing drawings.

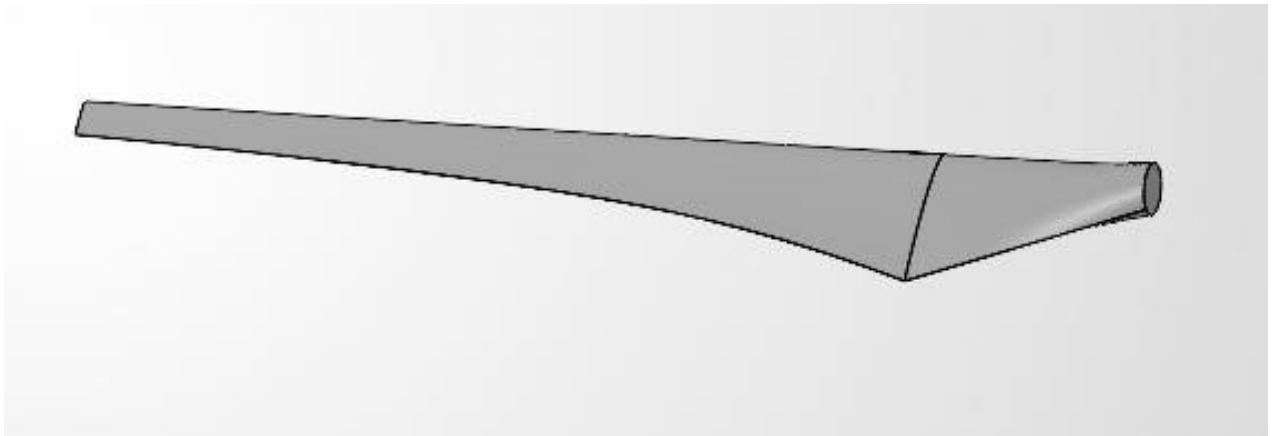


Figure 153 - Proposed Blade CAD Image

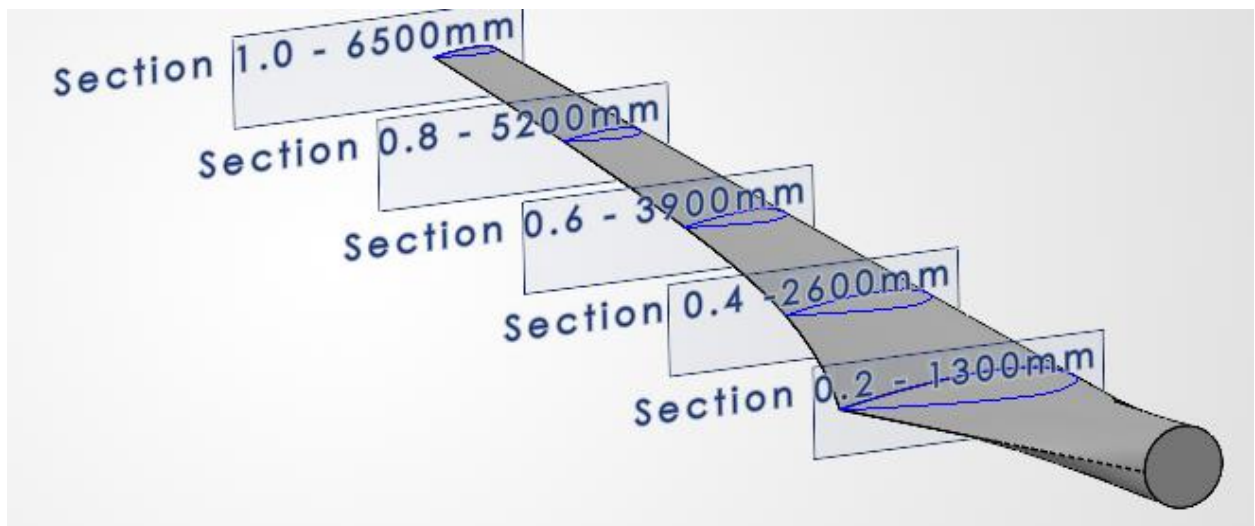


Figure 24 - Proposed Blade Design with Sectional Profile Details

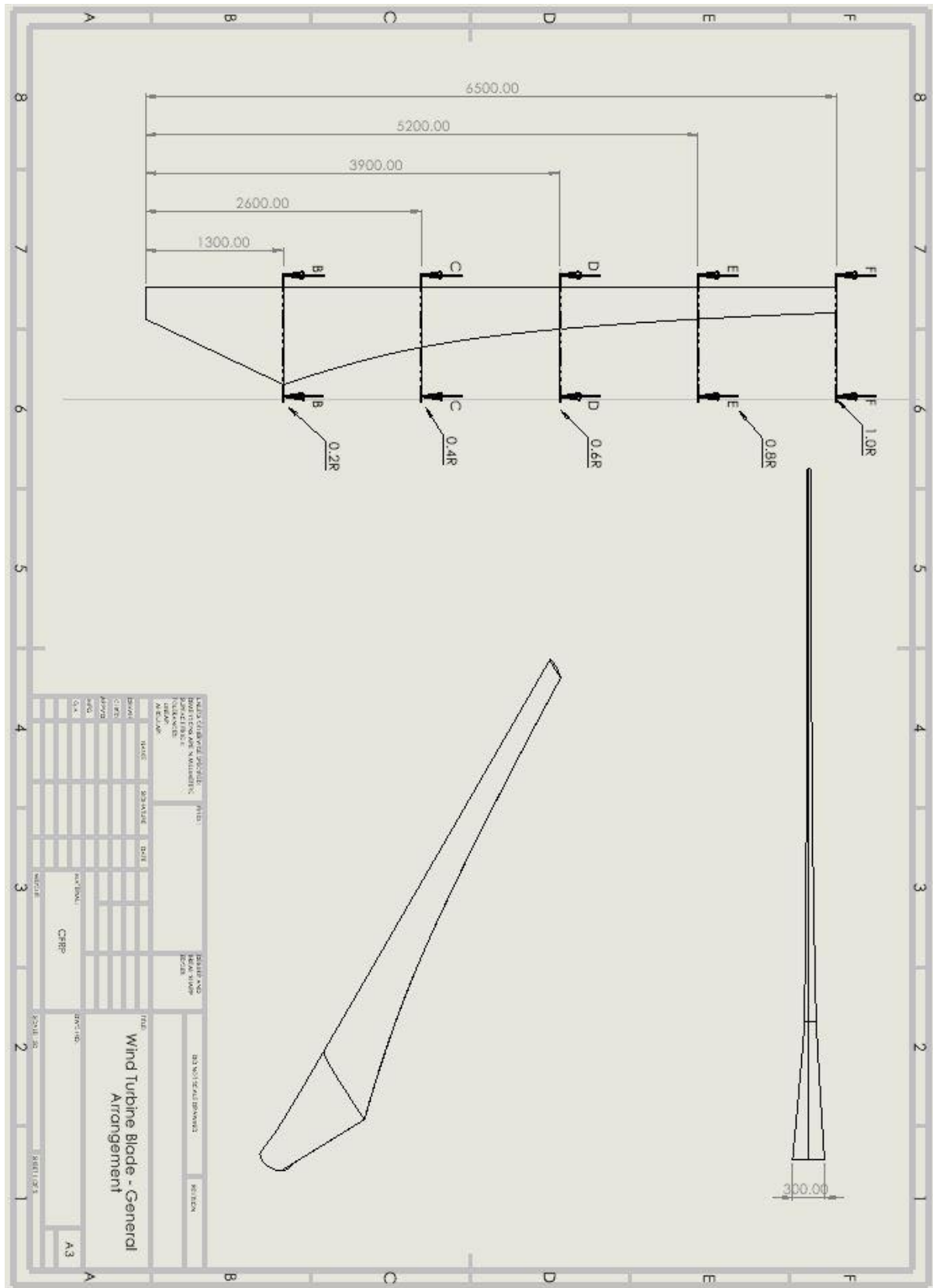


Figure 25 - Complete Blade Drawing

10 Conclusion and Recommendations

The research and development above demonstrate that aerodynamic geometry, material selection and manufacturing methods must be considered collectively when developing an efficient and durable wind turbine blade. The final 6.5 m blade that was calculated using a NACA 2412 profile ensuring a power output greater than 6935.16 W. The material comparison identified CFRP as the most suitable candidate due to its high strength, fatigue resistance and low density, despite its greater cost and limitations in recyclability. Vacuum infusion is recommended as the manufacturing process because it is suitable for large composite structures and relatively low tooling cost while producing high-quality laminates with low void content when careful process control is applied. Structural analysis produced a maximum root bending stress of 9.36 MPa and a torsional stress of 0.088 MPa under extreme wind conditions of 48 m/s. These stresses remained considerably below the CFRP material property limits, further supporting the selection.

Future work should validate the composite structure as a hollow design using FEA, investigate fatigue and cyclic loading, optimise laminate thickness and fibre orientation. Physical prototyping and aerodynamic testing should subsequently be used to validate the calculated performance. Investigation into improved recycling methods, recyclable fibres and resins systems is essential for greater sustainability.

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12 Appendices

Appendix A

By reviewing Hossain et al, (2014) experimental results in *Table 1* shows that NACA 4412 with a lift to drag ratio of 5.382 at 5° is greater than 6409 that achieved 0.66, later experiments in blade design by Gok and Alnimer (2024) indicates that NACA 2412 has a greater range in lift to drag ratio than NACA4412 across the angle of attack movement, this can be seen in *Figure 6*. Further reviews that profiles like NACA 6412 can provide even greater lift, but the stability of this blade will be decreased if used as the core profile of a large blade (Tira and Furqon, 2024). There are many more profile types such as Clark Y, RAF-15, C-80, Gottingen 398, and M-6 as indicated by Yurdusev et al, (2006).

Appendix B

Table 18 - 0.2 r/R Camber Line and Thickness

Base section (0.2) r/R Camber Line + Thickness	Column1	Column2	Column3	Column4	Column5	Column6	Column7
Section (X)	x (m)	Y_c/c	y_c (m)	Y_t	Y_t	Y_{upper}	Y_{lower}
0	0.00	0	0.00	0.00	0.00	0.00	0.00
0.1	0.09	0.00875	0.01	0.05	0.04	0.05	-0.03
0.2	0.18	0.015	0.01	0.06	0.05	0.07	-0.04
0.3	0.28	0.01875	0.02	0.06	0.06	0.07	-0.04
0.4	0.37	0.02	0.02	0.06	0.05	0.07	-0.03
0.5	0.46	0.019444444	0.02	0.05	0.05	0.07	-0.03
0.6	0.55	0.017777778	0.02	0.05	0.04	0.06	-0.03
0.7	0.64	0.015	0.01	0.04	0.03	0.05	-0.02
0.8	0.73	0.011111111	0.01	0.03	0.02	0.03	-0.01
0.9	0.83	0.006111111	0.01	0.01	0.01	0.02	-0.01
1	0.92	0	0.00	0.00	0.00	0.00	0.00

Table 19 - 0.4 r/R Camber Line and Thickness

Second section (0.4) r/R Camber Line	Column1	Column2	Column3	Column4
x (m)	Yc (m)	Yt	Yupper	Ylower
0.00	0.00	0.00	0.00	0.00
0.06	0.00	0.03	0.03	-0.02
0.11	0.01	0.03	0.04	-0.02
0.17	0.01	0.03	0.04	-0.02
0.23	0.01	0.03	0.04	-0.02
0.28	0.01	0.03	0.04	-0.02
0.34	0.01	0.03	0.04	-0.02
0.40	0.01	0.02	0.03	-0.01
0.45	0.01	0.01	0.02	-0.01
0.51	0.00	0.01	0.01	0.00
0.57	0.00	0.00	0.00	0.00

Table 20 - 0.6 r/R Camber Line and Thickness

Third Section (0.6) r/R Camber line	Column1	Column2	Column3	Column4
x (m)	Yc (m)	Yt	Yupper	Ylower
0	0	0	0	0
0.0396	0.003465	0.01854377	0.02200877	-0.0150788
0.0792	0.00594	0.02272067	0.02866067	-0.0167807
0.1188	0.007425	0.02376684	0.03119184	-0.0163418
0.1584	0.00792	0.02297992	0.03089992	-0.0150599
0.198	0.0077	0.02096434	0.02866434	-0.0132643
0.2376	0.00704	0.01807094	0.02511094	-0.0110309
0.2772	0.00594	0.01450907	0.02044907	-0.0085691
0.3168	0.0044	0.01038755	0.01478755	-0.0059875
0.3564	0.00242	0.00573296	0.00815296	-0.003313
0.396	0	0.00049896	0.00049896	-0.000499

Table 21 - 0.8 r/R Camber Line and Thickness

Fourth Section (0.8) r/R Camber Line	Column1	Column2	Column3	Column4
x (m)	Yc (m)	Yt	Yupper	Ylower
0	0	0	0	0
0.0302	0.0026425	0.01414197	0.01678447	-0.0114995
0.0604	0.00453	0.01732738	0.02185738	-0.0127974
0.0906	0.0056625	0.01812521	0.02378771	-0.0124627
0.1208	0.00604	0.01752509	0.02356509	-0.0114851
0.151	0.00587222	0.01598796	0.02186018	-0.0101157
0.1812	0.00536889	0.01378137	0.01915026	-0.0084125
0.2114	0.00453	0.011065	0.015595	-0.006535
0.2416	0.00335556	0.00792182	0.01127737	-0.0045663
0.2718	0.00184556	0.00437211	0.00621766	-0.0025266
0.302	0	0.00038052	0.00038052	-0.0003805

Table 22 - 1.0 r/R Camber Line and Thickness

Final Section (1)r/R Camber Line	Column1	Column2	Column3	Column4
x (m)	Yc (m)	Yt	Yupper	Ylower
0	0	0	0	0
0.0243	0.00212625	0.01137913	0.01350538	-0.0092529
0.0486	0.003645	0.01394223	0.01758723	-0.0102972
0.0729	0.00455625	0.0145842	0.01914045	-0.0100279
0.0972	0.00486	0.01410132	0.01896132	-0.0092413
0.1215	0.004725	0.01286448	0.01758948	-0.0081395
0.1458	0.00432	0.01108899	0.01540899	-0.006769
0.1701	0.003645	0.00890329	0.01254829	-0.0052583
0.1944	0.0027	0.00637418	0.00907418	-0.0036742
0.2187	0.001485	0.00351795	0.00500295	-0.002033
0.243	0	0.00030618	0.00030618	-0.0003062

Appendix C

Table 23 - Material Properties (Ansys, 2026)

Material	Density (kg/m³)	E (GPa)	Tensile (MPa)	Yield (MPa)	Fracture Toughness (MPa.m ^{0.5})	Fatigue Strength at 10 ⁷ cycles (MPa)	CO2 footprint kg/kg	Embodied energy MJ/kg	Recyclability	Price £/m³	Manufacturability
Aluminium 6061	2.71E+03	68.3	314	260	33	121.5	9.35	134	Good (3)	6.21E+03	4 (Good)
Structural Steel	7.85E+03	210	495	275	90.4	215.5	2.12	20.5	Good (3)	7.63E+03	4 (Good)
Silicon Carbide	3.15E+03	380	405	405	3.25	351	7.26	121	ok (2)	4.20E+04	2
Zirconia	6.10E+03	138	132.5	132.5	1.75	116	4.39	61.7	ok (2)	1.05E+05	2
GFRP	1.63E+03	19.3	251.5	251.5	13.55	100.8	6.95	120.5	ok (2)	6.98E+03	3
CFRP	1.57E+03	120.5	1.66E+03	1.66E+03	6.68E+01	1.01E+03	5.11E+01	7.30E+02	poor (1)	2.47E+04	3

Appendix D

$$T = \frac{1}{2} p V^2 A_C C_m$$

$C_m = 0.0488$ data provided by Guerrero et al, (2023)

$$A_C = \text{Area} \times \text{Mean of Area} = 6.644 \times 1.022 = 6.79 \text{ m}^2$$

T when $V = 25 \text{ m/s}$

$$T = \frac{1}{2} \cdot 1.225 \cdot 25^2 \cdot 6.79 \cdot 0.0488 = 126.85 \text{ Nm}$$

T when $V = 48 \text{ m/s}$

$$T = \frac{1}{2} \cdot 1.225 \cdot 48^2 \cdot 6.79 \cdot 0.0488 = 467.6 \text{ Nm}$$

