Department of Mechanical and Aerospace Engineering

Sustainable Development of Wind Turbine Blades: Investigating the use of sustainable materials in composites

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Abstract

This project set out to identify how the sustainability of wind turbines could be improved. A key challenge is to increase the extent to which its components can be reused or recycled. The project's focus was to investigate the feasibility of using sustainable composite materials in turbine blades.

A literature review identified potential sustainable materials that could be used to replace glass fibres in wind turbine blades. The materials selected were then modelled in a 42 m wind turbine, in typical operating conditions, and the performance of the blade was compared to a blade made of glass fibre and epoxy resin.

The review found significant scope for the environmental impact of wind turbines to be improved, particularly with regard to raw material acquisition and wastage. The sustainable materials that were found to be most promising were hemp and flax fibres and Polypropylene and Polylactic Acid for the matrix.

The computer modelling found that the turbine blades using sustainable materials do not perform as well as the glass fibre reference blade, particularly when considering the maximum deflection. As the sustainable material blades had smaller masses, a case study explored how the most promising sustainable composite performed when the mass of the blade was increased to be comparable to the reference blade. This resulted in performance that was closer to that of the reference blade with improved stiffness.

In conclusion, the project suggests that there is scope for more sustainable materials to be used for turbine blades. However, the results need to be interpreted in the context of the assumptions and simplicity of the turbine blade modelled. Future work needs to be undertaken to obtain a more definitive assessment. In addition, technological advances may lead to improved properties of the sustainable composites, such as fibre coatings for natural fibres and the use of hybrid composite materials, which may enable enhancements in performance.

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Nomenclature

Symbol	Description	Units
p	Pressure	Pa
G	Shear Modulus	Pa
E	Young's Modulus	Pa
µ	Poisson's Ratio	N/A
t	Tonne	t
Mt	Mega Tonne	t $x10^6$
GWh/a	Giga Watts hours per annum	N/A
v_r	Relative Velocity	m/s
ω	Angular Velocity	m/s
∇	Divergence	N/A
ρ	Density	kg/m^3
t	Time	s
$\boldsymbol{\tau}$	Deviatoric stress tensor	Pa
F_r	Radial force	N
m	Mass	kg
r	Radius	m
t CO_2 eq.	Tonnes of Carbon Dioxide Equivalent	t

1.0 Introduction

With the causes and effects of climate change becoming widely recognised as needing urgent attention, the need for greater sustainability in all walks of life is becoming increasingly important. The UN's 17 Sustainable Development Goals (SDGs) are a call to action for all countries to improve health and education, reduce inequality and spur economic growth while tackling climate change [1]. The seventh goal is Affordable and Clean Energy, which aims to "ensure access to affordable, reliable, sustainable and modern energy for all" [1]. To achieve this, enormous investment is needed to manufacture and install renewable energy generation.

Following international agreements including the Paris Agreement (2015), countries across the world are increasing the amount of renewable energy sources installed, with wind energy being at the forefront. A report by the International Energy Agency found that there was 1265 TWh of wind energy generated in 2018 and predicted it to rise to 3317 TWh or more by 2030 [2]. To reach this an equally large amount of wind turbines will be required. The manufacturing and installation of so many new wind turbines will require a vast amount of materials, and to be sustainable it is important that it is done using materials that cause the least negative impact on the environment.

Between 2000 and 2018, there was an increase from 17.7 GW of installed wind generation capacity to 561 GW, which is a compound annual growth rate of 21% [3]. Although growth is not expected to stay at this rate, as the installation of wind turbines continues and operational wind turbines increasingly come to the end of their life after 20-25 years [4], there are increasingly more issues arising with managing their sustainability. Some components of wind turbines can be reused or recycled; however, others are challenging to recycled or reuse, notably the turbine blades and the concrete base [5, 6]. This means that without different materials or new end of life processing techniques there will be a huge amount of material wastage. Liu and Barlow [7] found that with the current manufacturing and end of life practices, globally there will be 2.9 Mt of turbine blade waste a year and a cumulative total of 43 Mt by 2050.

Wind turbine blades are made using a mix of materials, but the most environmentally impactful are the composites due to the raw material acquisition and energy needed to manufacture them [8]. The most used composites are made from glass fibres with epoxy resin. However, carbon fibre tends to be used for larger turbine blades due to its superior strength. Other materials include woods such as balsa for the structural core and foam.

2.0 Literature Review

This section of the thesis reports on the literature review undertaken to inform and define the scope and objectives of this investigation. The main focus areas are the environmental impact of wind turbines (section 2.1), composite materials (section 2.2) and wind turbine blade FEA studies (section 2.3). Database searches were undertaken using The University of Strathclyde online library. The searches were narrowed down using keywords, and the sources used included textbooks, journal papers, test specifications and websites.

Text from each reference that was relevant to the investigation was copied into Microsoft Word documents for each main topic area, and the references were compiled using the software EndNote [9]. By collating the segments of text into documents, key findings were summarised and gaps in the literature were identified, which helped define the project's scope and objectives.

2.1 Environmental Impact of Wind Turbines

In this section, evidence relating to the environmental impact of wind turbines is considered. The section covers background information on wind turbines in section 2.1.1 and appraisal of more detailed research centred on LCA (Lifecycle Assessment) in section 2.1.2.

2.1.1 Background

The IPCC (Intergovernmental Panel on Climate Change) has predicted that, in an ambitious scenario, over 20% of the world's energy could be supplied by wind by 2050 [10]. In the appropriate conditions, operational wind turbines can produce energy with little or no impact on the environment. However, this does not mean that they lack an environmental impact, as there is a significant impact attributed to the manufacturing and installation of the wind turbines. As countries worldwide look to reduce their carbon emissions, the increase in the use of wind turbines means that the environmental impact from their manufacture and installation will become substantial [11, 12]. A study by Ozoemena et al. [13] found that a 114 MW onshore wind farm in South Wales had the GWP (Global Warming Potential) of 0.0018 kg CO_2 eq. per kW of energy generated over the lifetime of the wind farm. The energy generation of the wind farm was estimated to be 212 GWh/a yielding a capacity factor of 21% [13]. Therefore, the GWP each year is 382 t CO_2 eq. annually. When this is extrapolated for all the wind turbines installed globally in 2020, 743 GW [14], this equates to an estimated $2.5x10^6$ t CO_2 eq. per year, assuming the same capacity factors.

A study by Liu and Barlow [4] found that if the current manufacturing and end of life practices continue to be used, there will be 2.9 Mt of turbine blade waste produced a year and a cumulative total of 43 Mt by 2050. Unless changes are made to how wind turbines are manufactured and dealt with at the end of their useful life, it risks becoming a huge issue.

The size of wind turbine also has an impact on the overall impact of their manufacture and use. Bhandari et al. [15] showed that onshore wind farms' GWP (Global Warming Potential) is reduced with larger wind farms and turbines. This is due to the amount of energy generated with larger wind turbines being proportionately greater than the additional materials and energy needed to produce them [3, 15].

2.1.2 Lifecycle Assessments

A valuable way of assessing the environmental impact of any system or object is by conducting an LCA (Life Cycle Assessment). It can also assist in identifying where the environmental performance of a subject can be improved and inform decision-makers in industry or government about where investment should be focussed [16]. LCA analyses the whole life cycle by considering a broad range of impacts before quantifying them [17]. Such impacts include acquiring raw materials, transportation, production, use, recycling/reuse, waste treatment, and energy supply throughout the entire lifecycle [17]. The importance of LCA is highlighted by the role that it has been given in environmental regulations across the world, including ISO standardisation. As the movement towards reducing environmental impacts and shifting towards concepts such as the circular economy become more established, LCA's have become a fundamental methodology towards supporting this [18].

2.1.2.1 Wind Turbine LCA

There are numerous LCA's which investigate multiple types of wind turbines, including two and three-blade HAWT (Horizontal Axis Wind Turbines) and VAWT (Vertical Axis Wind Turbines), ranging from micro-scale rated at 1 kW to larger systems rated at 2 MW [8, 19-23].

The most widespread type of turbine currently in use and predicted to remain so for at least the near future is the three-blade HAWT [3]. Therefore, in this project, HAWT will be the focus. A typical setup is shown in Figure 1.

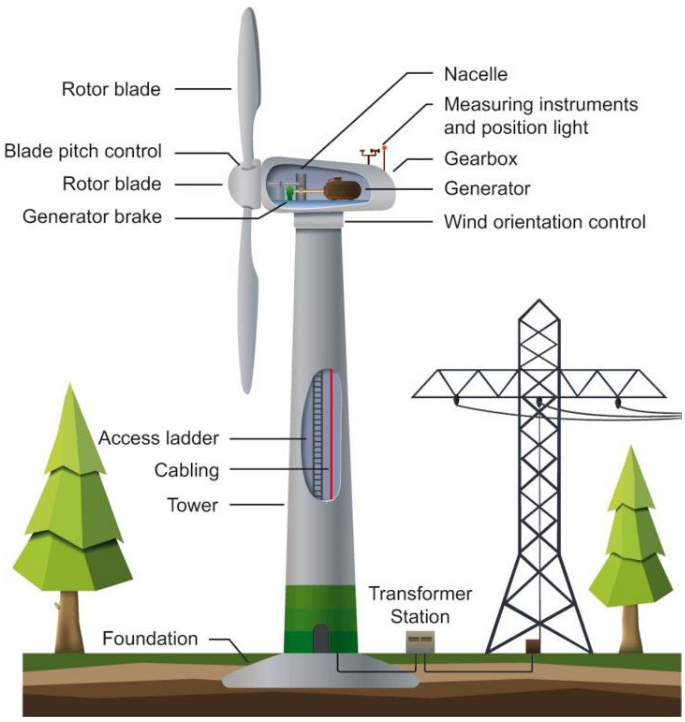


Figure 1 – Typical components of a wind turbine [24]

When conducting an LCA, each of the components can be considered separately or as one whole system. When looking to reduce the environmental impact of HAWT, considering each component at every stage of the LCA and then comparing them to each other, allows identification of the most impactful components and stages of a HAWT.

In a study conducted by Vargas et al. [20] on two 2 MW HAWTs in Mexico, the most impactful part of the wind turbine was found to be the tower and nacelle. In the wind turbines assessed, both these components were constructed of steel which, due to the large quantity required, contributed highly to their environmental impact. This is reiterated by Oebels and Pacca [21], where the tower was found to be the primary source of over half the CO_2 emissions associated with the material acquisition and manufacturing process of the wind turbines. The environmental impact of steel is due to the energy intensity of mining the raw materials required to produce steel, process it and manufacture it into useable parts.

However, an established method for reusing and recycling the steel from these parts exists so a high proportion of the environmental impact can be mitigated at the end of the turbines life [4].

A study by Guezurga et al. [25] found that up to 80% of wind turbines' components are recyclable. This is largely due to steel-based components such as the tower, hydraulics, generator and gears having an established method for recycling them [4].

However, other components such as the magnets, nacelle cover and wind turbine blades consist of materials with a composition and size that are harder to recycle [26]. Therefore, it can be argued that there is a need to focus development on reducing the environmental impact of the non-recyclable components.

The impact from the turbine blades is predominately from the raw material acquisition, the energy required, and the chemicals used in their manufacture [8], much of which is not currently recyclable. Sakellariou [27] described that wind turbine blades as "the sustainability blind spot of wind energy systems". Investigating how the environmental impact of HAWT blades can be reduced is the focus of this project.

2.1.2.2 HAWT Blade LCA

As shown in Figure 2, there are multiple components in a typical HAWT blade. These include the shell made from fibre and resin composites or laminate, a spar made of composite material, shear web consisting of a sandwich of materials and a core typically made from balsa wood.

The composite materials used in wind turbine blades are typically made up of a polymer matrix which can be thermoset plastic such as epoxies, vinyl esters, polyesters or thermoplastics [28]. There is a sandwich core for larger blades usually made of foams, such as polyethylene terephthalate (PET) or wood such as balsa. The composite shell must also be coated to protect the material against light/UV, moisture and impact from rain, hail and sea spray [29]. The coatings commonly consist of epoxy, polyester or polyurethane.

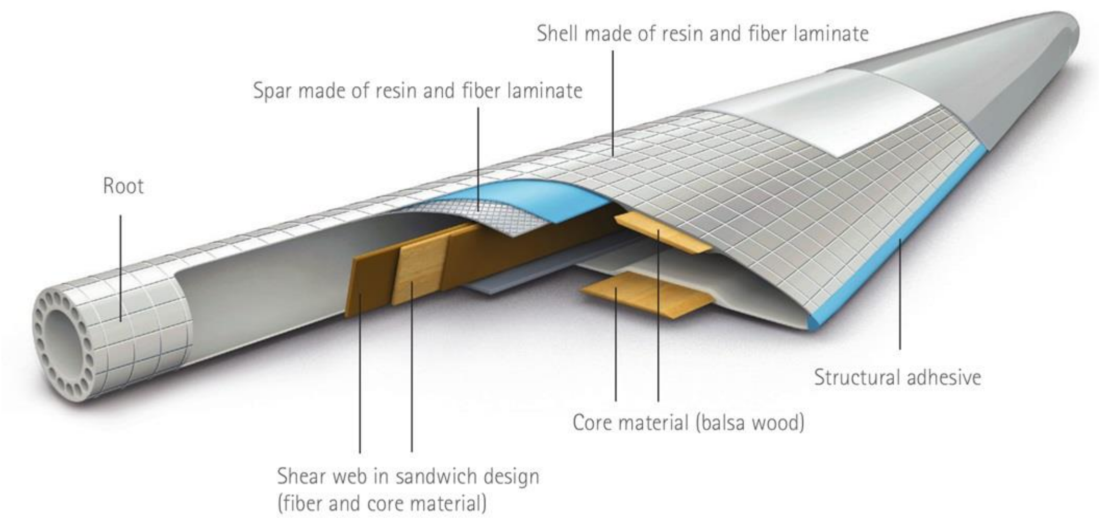


Figure 2 – The typical components and materials of a large wind turbine blade [30]

From an LCA conducted by Chiesura et al. [31], the most environmentally impactful lifecycle stage for wind turbines was the raw material sourcing associated with the composite materials used in the shell or turbine blade surface [31]. A study by Tomporowski et al. [32] found that the most negative impacts relate to the energy consumption, material usage and material waste during the manufacturing process. The study also found that offshore wind turbines are the more impactful due to the increased level of harmful substance emissions involved in their manufacture reflecting the requirement for higher performing coatings in the harsher offshore operating environment [32]. Therefore, the composite materials used in wind turbine blades will be the focus of this project to identify opportunities for replacement or modification to reduce the environmental impact.

The composite materials currently used in HAWT blades are predominantly composed of carbon or glass fibres with an epoxy resin matrix. Opportunities for replacement or modification of materials to reduce the environmental impact will be discussed in section 2.2.

2.2 Composite Materials

In section 2.2.1 below, the theory is discussed on using composite materials for wind turbine blades, their history, how they work, why they are useful and what they are used for. Section 2.2.2 evaluates the impact on the environment from composite materials and how this can be reduced by using bio-composites.

2.2.1 Background

Composite materials are composed of at least two constituent parts to improve their properties compared to their homogeneous form. In artificial composite materials, the two parts are commonly fibres for reinforcement and a surrounding material matrix [33]. These constituent parts present the opportunity for anisotropic materials, which need to be considering when designing and manufacturing components using composite materials. This allows the loading of the component to be aligned with the direction that the material is strongest to optimise the performance of the composite material. Figure 3 shows how unidirectional composite plies can be laminated to produce a laminated composite material that has the required material properties in the required direction.

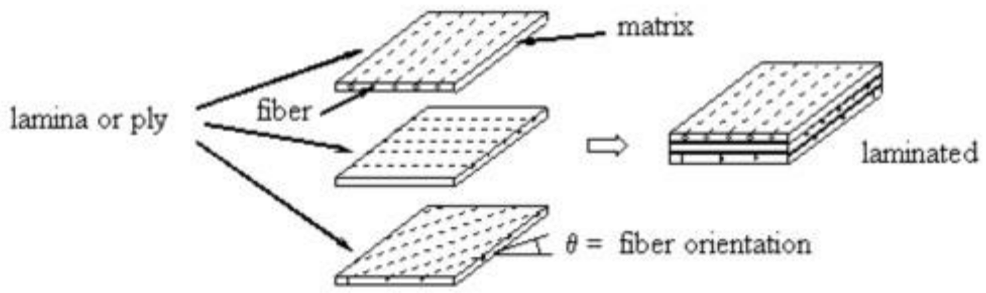


Figure 3 - Diagram of how laminate composite materials are constructed [34]

Composite materials have been used throughout history, with some of the first examples being bricks reinforced with straw during the time of the Pharaohs in Egypt [35]. Within the last 70 years, composite technology has improved due to polymer material development, allowing materials such as glass fibre reinforced polymers (GFRP) and carbon fibre reinforced polymers (CFRP) to be produced [36]. Such modern composites often have unique properties that are particularly useful in the construction, automotive, wind energy and aeronautical industries [37].

The reinforcing fibres or particles give strength and stiffness and are usually small compared to the matrix of the material. They can be in single layers in continuous forms, such as unidirectional, bidirectional and woven or in discontinuous forms, such as random orientation or preferred orientation. Fibres can also be stacked into multiple layers to produce laminates and hybrids designed to give the material the required properties for the application [33].

The matrix is continuous and usually has a lower stiffness and strength compared to the reinforcement. The primary function of matrices is helping to distribute loads by holding the reinforcement together and allowing the transmission of force throughout the material [36].

Other functions include carrying interlaminar shear, assisting in controlling the composite's chemical properties, and protecting the reinforcement from mechanical damage [36].

Parameters that are important to the composite material's properties include the concentration of the reinforcement constituent compared to the matrix and the reinforcement's size, shape, distribution and orientation. The concentration or fibre volume fraction is the proportion of fibres in the material. A higher proportion leads to stronger and stiffer composites [38]. However, the proportion of fibres cannot be so high that there is not enough matrix material to bond the composite together sufficiently [39].

The wind energy industry is one of the most significant users of composites materials, which are primarily used in the nacelle and turbine blades [40, 41]. The commonly used composite material in wind turbine blades is GFRP. CFRP is used for larger blades that require superior material properties.

When designing a wind turbine blade, there are three main requirements which make composites the most suitable type of material to use [42]. The first of these is that the aerodynamic performance is maximised by increasing material stiffness. The second is that the gravitational forces should be reduced by using low-density materials. The final requirement is that material degradation should be avoided by selecting materials based on their fatigue life.

In GFRP, glass fibres are used for reinforcement as they have good strength and stiffness. Glass fibres are produced by melting the raw material, which is silica (SiO_2) based, before extruding through bushing under gravity [33]. In CFRP, the reinforcement is carbon fibres which can be up to five times stronger than glass fibres [33]. They can be produced in many ways; however, two primary processes are used to produce them commercially. The first is to make them from polyacrylonitrile (PAN) fibres, the preferred process for producing carbon fibres with a high Young's modulus [33]. The second method is to produce them from mesophase pitch. The pitch, which is a complex mixture of thousands of different hydrocarbons, is heated in this process. This causes condensation reactions which form large, flat molecules which tend to align parallel to each other [33].

For both GFRP and CFRP, the matrix material used is a polymer. There are two main types of polymer matrices; thermosetting and thermoplastics. The polymers most commonly used are epoxy, PP (polypropylene), polyesters and nylon [33]. The material selection for the matrix is often based on properties such as ease of manufacture, thermal expansion coefficients, Young's modulus, Poisson's ration and Tensile strength.

GFRP is a widely used material as it combines high tensile strength with low density, which allows the wind turbine blades to withstand the mechanical load requirements. In addition, it can be formed to ensure the blade performs aerodynamically [28]. GFRP is also less expensive than CFRP and can easily be affixed with other essential components, such as leading-edge protection and lightning protection.

2.2.2 Sustainability and Bio-Composites

In section 2.2.1, it was explained that most of the composite materials used for wind turbine blades are GFRP or CFRP. These materials have an environmental impact as the fibres come from non-renewable sources, and the polymers are predominantly derived from crude oil.

The recyclability of these components is poor due to the chemical bonds and structure of the materials. It is difficult to recycle thermoset plastics, such as phenolic resin or epoxy resin, and the corresponding composite materials due to the covalently cross-linked networks. Consequently, they cannot be dissolved, melted, remoulded or reprocessed [43]. Although there has been a large amount of research into developing ways to recycle composite materials, such as by using covalent adaptable networks, pioneered by Montarnal et al. [44], this has not yet led to commercially viable, scalable solutions.

There has also been research into alternative end of life options for wind turbine blades other than recycling. An LCA conducted by Nagel et al. investigated the end of life solutions for wind turbine waste [45]. It found that when comparing the solutions of co-processing in cement kilns in Germany, co-processing in Ireland and landfill in Ireland that co-processing is six times more environmentally beneficial than landfill. However, more research is needed to determine how co-processing compares to other end of life reuse or recycling processes. Co-processing is a process where some of cement raw materials are replaced with chopped or ground up GFRP allowing the wind turbine blade to be fully used up [11]. This is a promising process however it vastly reduces the value of the materials due to the disparity in price between cement and GRFP.

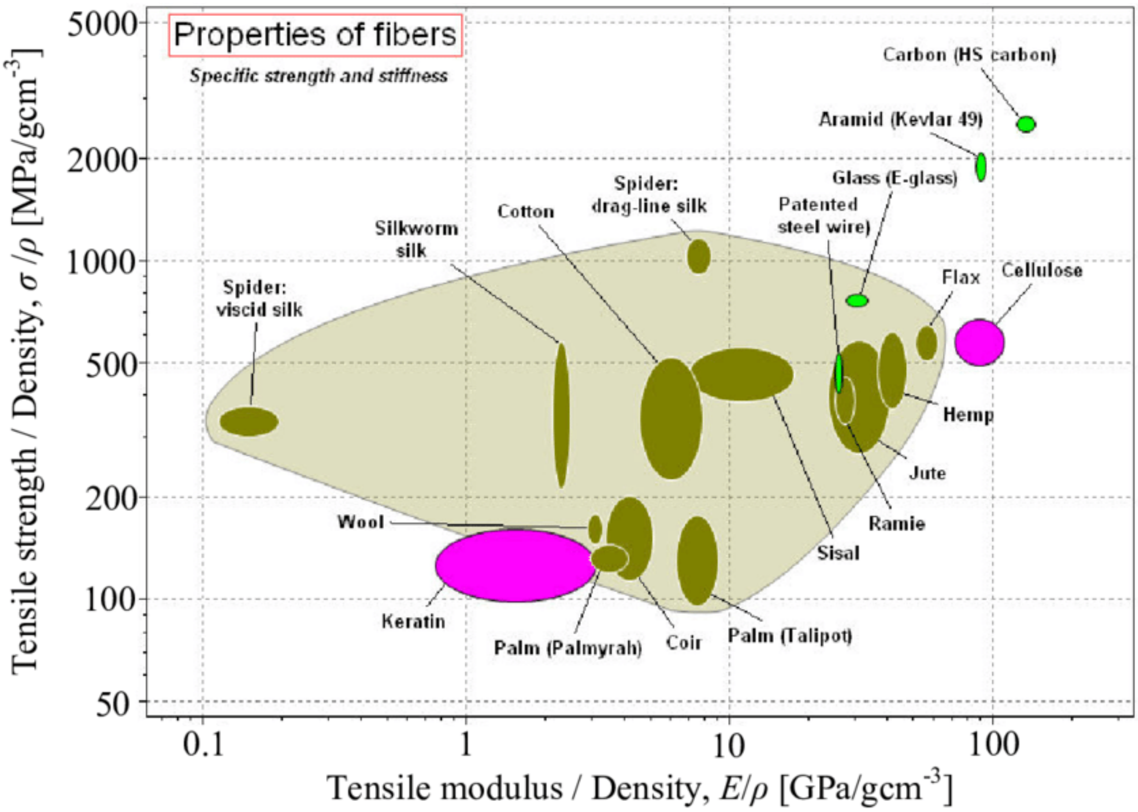


Figure 4 - Ashby plot comparing natural and synthetic fibres [39]

Significant research is going into sourcing more environmentally friendly materials for composites for wind turbine blades. Studies have been conducted on natural fibre composites, with flax, hemp, jute, bamboo, and sisal being some of the most promising [46-50]. These studies have found that natural fibre composites have advantages such as low density, cost, and environmental impact. However, there are challenges, such as being a less mature technology, less each to work with during manufacturing and less easily defined material properties. Pertinently, some natural fibre composites were found to have comparable material performance when compared to GFRP, as shown in the Ashby materials plot in Figure 4. Some natural fibres have comparable tensile strength to density properties to glass fibres, and some have better tensile modulus to density properties. Hence, if the manufacturing of these natural fibre composites occurred as successfully as GFRP, they could potentially replace them.

For the matrix material, it is also possible to use bio-sourced materials rather than synthetic-based resins, so reducing environmental impact. This includes materials such as PLA (polylactic acid) which are derived from renewable resources such as corn and sugar beets [51]. Under specific environmental conditions, PLA can degrade to carbon dioxide, water and methane within two years [51]. This is a significant advantage over petroleum-based polymers, but the gases released will still have a negative effect on the environment.

A benefit of using natural fibre composites is that they could be designed to be more recyclable than GFRP and CFRP [52]. Natural fibres are biodegradable naturally or can be incinerated for energy recovery at the end of their useful life. These processes are easier and more environmentally friendly than reusing or recycling synthetic fibres, but the incineration of natural fibres will increase air emissions [53].

Using thermoplastic resins makes it possible to reshape the resin part of the composite by heating it [54]. This involves grinding the resin off and into small particles that can be mixed with virgin thermoplastic material and reused in composite materials [54]. Thermoplastic resins include polyethylene (PE), which already has high worldwide production, meaning it may be possible for use in wind turbine blades. However, due to the large viscosity of traditional thermosetting resins, they can be unsuitable for use in the vacuum infusion processing commonly used to manufacture composite wind turbine blades [52].

Despite promising material properties, there are some issues with natural fibre composites that need to be addressed. It has been found that plant fibre composites consistently produce lower fibre volume fractions than synthetic fibre composites due to the poor packing ability of plant fibres [55]. Therefore, it may be difficult to obtain the maximum exploitable properties from plant fibre reinforced composites.

Another pertinent concern with natural fibre composites and their use in wind blades is moisture absorption. When composite materials with natural fibres absorb moisture, this may have several adverse effects on the long-term performance. This includes a deterioration in their mechanical properties, conditions where the fibres can begin to degrade and change the fibres’ dimensions [56]. A study by Robertson et al. [57] has shown that as the natural fibre composites absorb moisture the Young’s modulus increases whilst the impact strength and elongation at break percentage decreases. They found that the tensile strength increased slightly, although the response was not equal between the different types of natural fibres [57]. This will have to be considered if natural fibres are used in wind turbine blade application, as they are often subjected to harsh environments with large amounts of precipitation. However, investigations into coatings such as maleic anhydride polyethylene have shown positive results, which could reduce the moisture absorbed by the natural fibres [57].

In summary, there are recognised potential positives and negatives to using bio-based materials in composites for HAWT blades. To investigate whether bio-based composites can perform comparably to FGRP, this project will compare the mechanical performance of the composite materials when used for a wind turbine blade. To do this, FEA (Finite Element Analysis) will be conducted, which is discussed in 2.3.

2.3 Wind Turbine Blade and Natural Fibre FEA Studies

As the number and size of wind turbine blades manufactured continue to increase, the design of the turbines has developed progressively to ensure a consistent or improved level of performance. A cost-effective and fast method to conduct this analysis in the early stages of development is performing FEA. FEA is a computer-based numerical tool that is used to simulate engineering or scientific problems. For a problem involving a wind turbine blade, the solid is discretised into smaller elements or volumes, allowing the problem to be analysed for each element rather than trying to solve it for the full geometry.

There are numerous FEA research papers on a wide range of topics regarding HAWT blades. These were read, and some were used to help define the objectives and methodology of this project [58-60]. Due to the high functionality and depth of research using ANSYS, it was chosen as the software used for the analysis in this project. The version that has been used in this project is ANSYS 2020 R1 [61] which is the standard licence currently held by the University of Strathclyde.

Studies that have modelled wind turbine blades have shown that using FEA is an effective way to predict the mechanical response of the materials [49, 58, 59, 62-64]. These studies have focused on the deflection of the wind turbine blade under mechanical and aerodynamic loads, max stresses and strain, max von Mises stress, and modal investigations.

There are a range of variables that can be used in the FEA studies of HAWT blades. One of the most important is the wind speed, which gives the aerodynamic pressure acting on the blade. This can be set as the rated wind speed of the wind turbine, the cut-out wind speed or if damage calculations are being assessed, storm wind speeds can be used. The wind speed significantly affects the pressure, and so a higher wind speed will cause the results such as deflection, stress, strain, and damage value to be larger.

2.4 Summary

In summary, the literature review has found significant scope for the environmental impact of wind turbines to be improved, particularly with regard to the impact from raw material acquisition and wastage. Wind turbine blades currently have poor recycling and reuse options. There is little literature on the viability of sustainable materials for use in wind turbine blades and the extent to which biomaterials can be used to reduce their environmental impact. The next step in this project was to select the materials for use in the FEA analysis; this is discussed in section 4.0.

3.0 Aims and Objectives

The aim of this project is to investigate whether sustainable materials can be used to replace the materials currently being used in wind turbine blades to reduce their negative impact on the environment. The gap identified in the literature review will be addressed by using FEA in this investigation to compare variables such as the deformation, stress and strain of the different materials selected. The wind turbine that will be investigated in this study is a typical 2 MW, three blade HAWT under typical, rated wind conditions.

4.0 Material Selection

In this section, the selection of materials for the modelling is considered. Materials were selected for the fibre and matrix constituents of the composite materials used when modelling the wind turbine blade. Materials data was explored from literature identified during the review (subsection 2.2) and research into materials with a lower environmental impact that could replace GFRP for use in wind turbine blades.

The review found a large amount of variability in the material properties data for natural fibres. This can be explained by natural variations in several parameters, including the quality of the fibres' source and disparity in the fibre extraction locations from the source. Other factors such as moisture content, fibre diameter and density also have an effect and so can lead to significant variations in the material properties [12]. Often ranges were given in the data found for the material properties. In this scenario, an average for the range was used, ensuring that the value used is likely to be valid.

Although there have been some promising results when using surface treatments on natural fibres to improve their mechanical properties [57, 65], the material properties without treatment will be used for simplicity in this project.

4.1 Fibres

The material properties for the three fibres chosen for the composite modelling are shown in Table 1. Glass fibres were used as the baseline fibre that are commonly used in wind turbine blade manufacturing. Hemp and flax were selected as the natural fibres for comparison because of their high performing specific mechanical properties [66] and the reduced environmental impact that they have over glass fibres [67].

Table 1 - Material properties of fibres selection for analysis [70]

Material	Young's Modulus (GPa)	Poisson's Ratio	Shear Modulus (GPa)	Density (g cm^{-3})	Specific Tensile Strength (GPa/g cm^{-3})	Fibre diameter (µm)
E-Glass Fibres [68]	73	0.22	29.9	1.8	41	8 [69]
Hemp Bast Fibres	64	0.26	25.4	1.5	43	20 [65]
Flax Fibres	55.7	0.26	21.2	1.5	36	15.3

Table 1 shows that glass fibres have the highest Young's modulus, followed by hemp and flax. This shows that glass fibres are the stiffest but as the density of the glass fibres is higher than that of the natural fibres the specific tensile strength is comparable for glass fibres and hemp fibres with flax slightly lower. Hence, natural fibres could be suitable to replace the glass fibres from this assessment of their specific tensile strength.

Information on the fibres and their properties are further explained in subsection 4.1.1 for the glass fibres, subsection 4.1.2 for the hemp fibres and subsection 4.1.3 for the flax fibres.

4.1.1 Glass Fibres

Glass fibres were chosen for this study as they are the most frequently used fibres for composites used in wind turbine blades. They are commonly used in the form of continuous fibres or chopped strand [40]. There are multiple types of glass fibre, including E-glass, S-glass, and C-glass. Their different chemical compositions give them varied properties that make them suited to specific applications. E-glass will be used in this study because it is the most commonly used glass fibre in wind turbine blades [11], although the more expensive S-glass is used when extra stiffness is required as it has a higher Young’s modulus (9 GPa).

The Young’s modulus of glass fibre is relatively stable, but the tensile properties can be widely scattered [66]. The values for this and other parameters were taken from the ANSYS Engineering Data [68]. The diameter of the glass fibres is typically between 3.8 and 20 µm. In this project, the diameter will be set to 8 μm as this is a standard size for the glass fibres used [33]. The manufacturing process for glass fibres is explained in 2.2.1 and is an established material for use in wind turbine blades.

4.1.2 Hemp Fibres

Hemp fibres can be used as reinforcement in composites due to its high strength and stiffness being comparable to glass fibres [65]. The hemp fibres are taken from the stem of the plant, specifically the bast fibres, which is where the fibres with the best mechanical properties are found [65]. The bast is a specific region of the stem where the fibre have superior properties [71]. The range for the Young’s modulus of hemp fibres found in the paper by Chaudhari and Bhole [70], was 58-70 GPa giving an average of 64 GPa.

The average fibre diameter of hemp is 17-23 μm [65]; the average value of 20 μm will be used in this project. Although hemp has a similar chemical composition as flax it has better moisture resistance [65]. Another important parameter for is the length of the fibres as longer fibres can improve the mechanical properties of composite materials [12]. Unlike synthetic fibres such as glass, natural fibre lengths are not customisable. The fibre lengths for bast fibre have been measured to be in the range of 5-55 mm [12]. Hemp fibres are produced by extracting the fibres from the stalks by retting before being processed, which involves mechanical processes such as milling and cleaning before being dried [72]. These processes are well designed, but they can be aggressive and lead to damage within the fibre wall which can severely affect the mechanical properties [73].

4.1.3 Flax Fibres

Flax bast fibres can also be used as reinforcement in composites, although its strength and stiffness are slightly lower than hemp. A study by Lefeuvre et al. [66] concluded that flax fibres are suitable to replace glass fibres, with the flax fibres tested being on average 15.3 µm in diameter and the average Young's modulus was 55.7 GPa. The range for the Young's modulus of flax fibres reported in the paper by Chaudhari and Bhole [70], was 27-80 GPa giving an average of 53.5 GPa. This shows that the Young's modulus found by Lefeuvre et al. [66], of 55.7 GPa is likely to be valid and will be used as the value for the modelling section of this study along with the value of the average diameter of the fibres. The length of flax fibres has been found to be 5-900 mm which is significantly longer than hemp [12].

The disparity of the Young's modulus of the flax fibres was found to be a third larger than that of a comparable batch of glass fibres in the study conducted by Lefeuvre et al. [66]. This suggests a potential issue with using flax fibres for structural composites, and there may need to be additional quality control to ensure that the fibres selected have the required properties. The cause of the differences was not known but hypothesised to be due to the various lumen sizes, differing biochemical compositions, or difficulties in measuring the diameter of the fibres [66]. This highlights key issues that may need to be investigated before natural fibres composites can be used in wind turbine blades.

It was found that the tensile properties of the flax were reproducible despite periods of drought or excess rain during the vegetative period [66] showing that external factors such as the weather may not have a negative effect. This is confirmed in a study by Baley and Bourmaud [74], who found that although there is significant variation between batches of flax fibres, none of them was very weak with fibres of poor mechanical property.

The production of flax and hemp fibres globally is 830000 and 214000 tonnes respectively [75]. Hence, there is already an established market and supply chain suggesting the infrastructure is in place for the fibres to be used widely. Similar to hemp bast fibres, flax fibres are also extracting by retting before being processed to produce dry fibres.

4.2 Matrix

Table 2 - Material Properties of matrix materials selected for analysis

Material	Young's Modulus (GPa)	Poisson's Ratio	Bulk Modulus (GPa)	Shear Modulus (GPa)	Tensile Yield Strength (MPa)	Density (kg m^{-3})	Ply type
Epoxy Resin [68]	7.78	0.35	4.2	1.4	54.6	1160	Isotropic
PP [33]	1.2	0.36	1	0.4615	30	900	Isotropic
PLA [72]	1.28	0.36	1.5238	0.47059	70	1280	Isotropic

Table 2 shows the material properties for the three matrix materials that were chosen for the composite modelling. Epoxy resin was chosen as the first material as it is the most widely used polymer matrix material in composites [76]. Therefore, it is a good baseline material that can be used to compare to less environmentally impactful materials. There are many variations of epoxy resins, all with different chemical compositions and material properties. The epoxy resin preloaded in ANSYS 20.0 Engineering Data [68] will be used for this project.

The properties of the matrix materials show that the epoxy resin has a higher Young's modulus showing that composites using epoxy will be stiffer. The other two materials have very similar properties; however, the density of polypropylene is lower than that of PLA and epoxy. All the matrix materials are compatible with the fibres. However, thermoset and thermoplastic matrix materials often need to be manufactured differently. The ideal way for natural fibre composites to be manufactured is using prepreg technology or vacuum infusion which can be done using thermosets [77]. Thermoplastic must use injection moulding or compression moulding which is less desirable and can lead to porosity issues [77].

The matrix materials and their properties are shown in subsection 4.2.1 for epoxy resin, subsection 4.2.2 for polypropylene and subsection 4.2.3 for polylactic acid.

4.2.1 Epoxy Resin

Epoxy resin was chosen as the first matrix material for modelling as it is a well-established matrix material and is the most commonly used in composites [33]. There are many types of epoxy resin, and their mechanical properties can vary depending on their chemical composition. Epoxy resins are petroleum-based and are produced through the reaction between bisphenol A and epichlorohydrin. They cannot be recycled after use due to highly cross-linked molecule chains [78].

Epoxy resins are widely used as the matrix material due to their versatility which makes them suited to being used in several composite manufacturing processes [78]. These processes are commonly either wet resin or prepreg. Epoxy resins also have good mechanical properties for use as a matrix material, such as strength, high modulus, good durability and superior thermal and chemical resistance [78]. They also combine well with reinforcement fibres to produce a strongly bonded composite.

4.2.2 Polypropylene

The second resin that was chosen for the study was polypropylene (PP). PP was chosen because it is one of the most widely used thermoplastics for matrix materials due to its excellent characteristics for use in composites [79]. It is primarily produced during the cracking process of crude oil [79]. As it is thermoplastic, it is possible to recycle it by reheating it and mixing it with virgin material. Although it can degrade in high heat, this is highly unlikely to be an issue when used in turbine blade composites.

PP is a well-established material for use as a matrix material in composites. However, as it is a thermoplastic, it is more difficult to process for large composite components than thermoset polymers such as epoxy due to the material being polymeric before the composite is fabricated [33]. This makes it difficult to use PP in a large component such as a wind turbine blade. However, in this project, it will be assumed that it would be possible to produce a wind turbine blade with a composite material using PP as the matrix.

4.2.3 Polylactic Acid

PLA (Polylactic acid) was chosen as it is the most widely used bioderived polymer [80]. PLA is a class of crystalline biodegradable polymer that is derived from renewable resources such as corn, wheat and sugar beets [51]. It has a relatively high melting point and excellent mechanical properties [51]. PLA is derived from lactic acid and obtained by polycondensation [81]. It has been calculated that PLA requires 25-55% less energy to produce than petroleum-based polymers [82]. The properties of PLA resins can vary due to the component isomers, processing temperature, annealing time and molecular weight [83].

When exposed to specific conditions PLA is biodegradable and has been found to be in the "late stages" of biodegradation after 90 days in compost conditions [84]. Thus, when it is combined with natural fibres this then gives a completely biodegradable composite material. However, if PLA is used in a wind turbine blade application it is likely that a coating will be needed to ensure that there is not excessive degradation of the material due to the often-harsh operating conditions of the wind turbines. This is dependent on the conditions required to degrade the PLA which is dictated by the chemical composition of the PLA used. There is also a worry that it will degrade quicker than no bio-based resins would need to be investigated before using PLA on a large scale for wind turbine blades.

4.3 Summary

In summary, the material selection section has outlined that the reinforcement fibres used in this investigation are glass fibre, hemp bast fibres and flax bast fibres. The glass was selected as a comparison to judge the natural fibres against as glass is currently the most widely used fibre for composite material wind turbine blades. The mechanical properties show that natural fibres have slightly lower Young's modulus. However, they have a lower density which means that they could perform comparably. The matrix materials chosen are epoxy resin, PP and PLA. The epoxy was chosen as it is the most widely used matrix material and will be compared with the other matrix materials. PP was chosen as it is thermoplastic which means that it can be recycled after use. PLA was chosen as it is the most widely used biodegradable matrix material and is also derived from plants which means it has a less negative impact on environmental impact.

5.0 Methodology

This section describes the methodology and reasoning behind it to undertake the modelling for this investigation. In subsection 5.1, the wind turbine blade and geometry that was selected will be considered. Subsection 5.2 explains how the Material Designer Function was used to create the unique composite for the study. Subsection 5.4 describes how the load cases were created in Ansys for the aerodynamic loading from the wind and the mechanical loading due to the movement of the wind turbine blade. Subsection 5.5 covers the main assumptions that have been made in the modelling to simplify certain aspects of the investigation. Subsection 5.6 describes how the meshes were generated and subsection 5.7 evaluate the quality of the meshes. Subsection 5.8 describes laboratory work that ideally would have been conducted to improve the validity of the findings but was beyond the scope of the current investigation owing to constraints that prevented access to laboratory facilities.

5.1 Geometry

The geometry of the wind turbine blade used in this study was based on those currently in use. Lantz et al. [85] found that the most common turbines installed globally are between 1.5 and 3 MW, although installed turbine capacity sizes are increasing. Hence, the blade chosen for the modelling is 43.2 m in length, which is typical for a 2.0 MW turbine with three wind turbine blades. The geometry of the wind turbine blade was taken from a SimCafe tutorial, an online platform for learning how to complete FEA by Cornell University [86].

The geometry of the turbine blade in shown in Figure 5Figure 5. The figure gives a simple design for a turbine blade made up of the outer surface shell and a single thickness spar that runs through the inside of the blade. For simplicity, in the current investigation both these parts will be considered as consisting of the same composite material. In reality, as shown in Figure 2 (page 6), a turbine blade is made up of multiple materials, but as this study focuses on comparing the composite materials, a simple geometry with one material is acceptable.

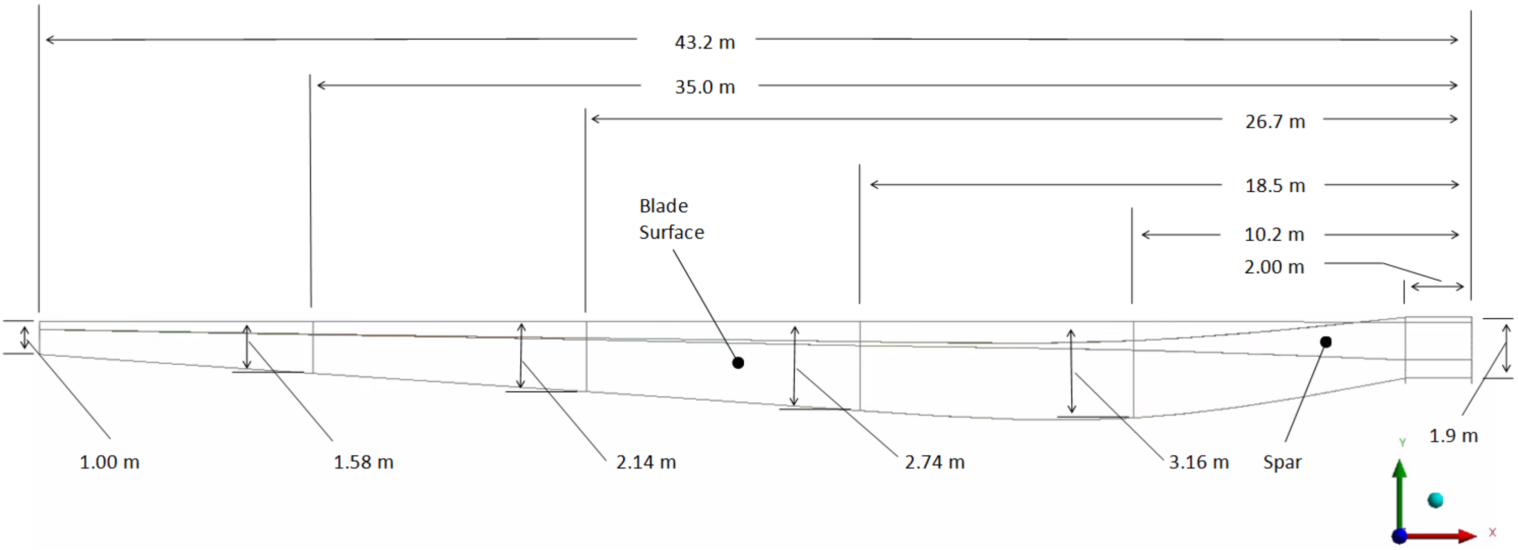


Figure 5 – Geometry of the turbine blade used in the modelling

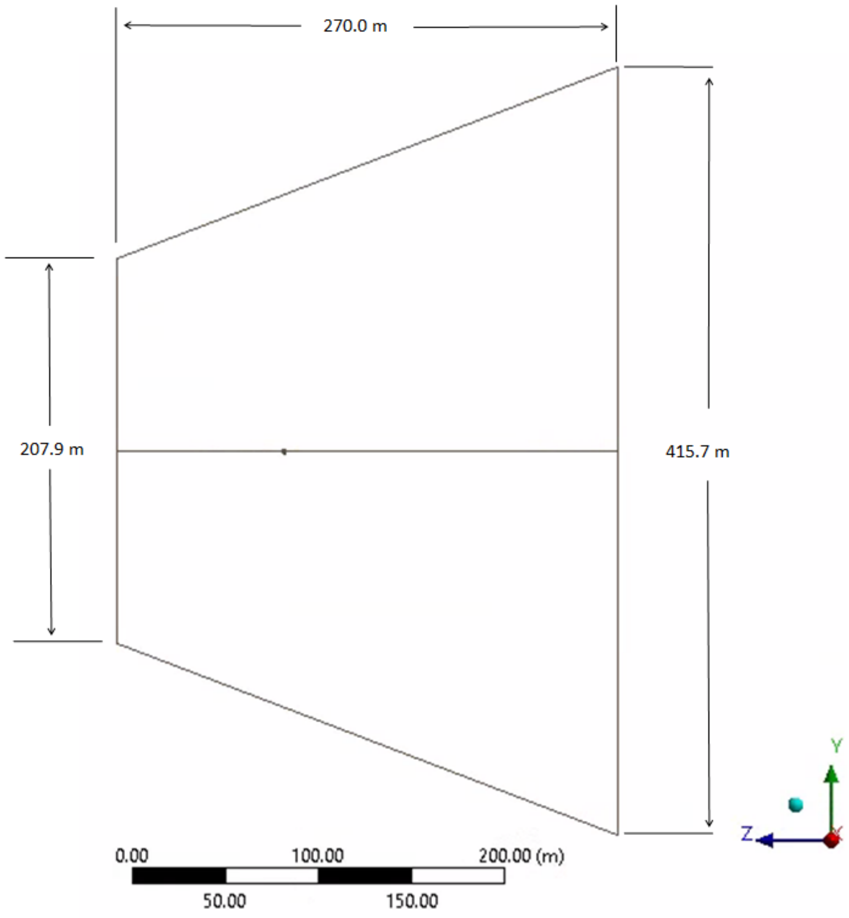


Figure 6 – Geometry of the fluid domain

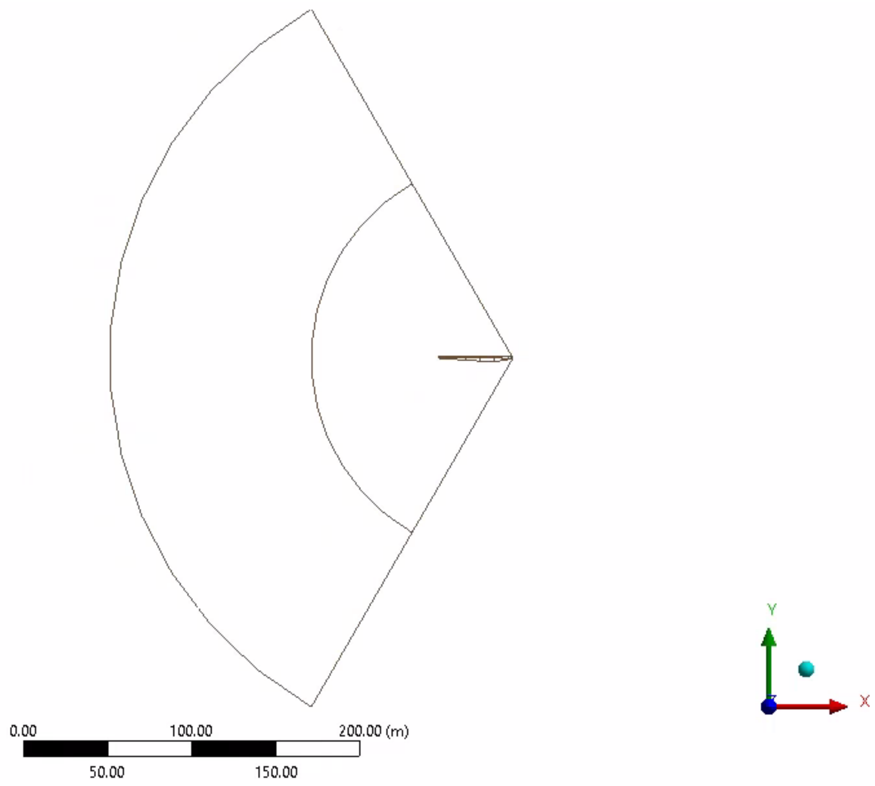


Figure 7 – Front view of the fluid domain geometry

The geometry of the fluid domain surrounding the wind turbine blade is shown in Figure 6 and Figure 7. The domain is significantly larger than the turbine blade to allow the fluid's interaction before and after the blade to be completely established. The domain represents a third of a complete domain that would exist for a three-blade wind turbine to reduce the computing power required for calculating the results. The primary purpose of this domain geometry is to calculate the aerodynamic pressure on the turbine blade, which is discussed further in subsection 5.4.1 (page 25).

5.2 Material Designer

To create the unique composite materials in ANSYS the Material Designer function was used. The Material Designer application enables modelling and analysis of microstructures and deriving homogenised material properties for an RVE (Representative Volume Element) [87]. The RVE is a valuable way to model composite materials as it vastly reduces the number of elements needed to simulate a composite. It does this by simulating the RVE and assuming that the microscale structure is consistent throughout the material. These microstructures can be designed to simulate composite materials that can be altered with variables such as RVE type, fibre volume fraction, fibre diameter, and geometry type.

The RVE chosen for the materials included in this study were User Defined Composite. This creates a composite material consisting of a matrix and reinforcement fibres which are all in the same direction. The fibre volume fraction that was used for each of the materials created was 70% for glass fibre and 60% for natural fibres [38]. These values represent the approximate highest practical fibre volume fraction for synthetic and natural fibres. The fibre volume fraction is the space within the RVE occupied by the fibre material. The fibre diameter is a characteristic of the material used. This is found from experiments and literature and so varied for each fibre. The values used for these are shown in Table 1.

The geometry type chosen in this study was hexagonal; a central fibre in each square element with a quarter of a fibre in each corner of the element, as shown in Figure 8. The hexagonal RVE was chosen to allow a higher fibre volume fraction for the composite [33].

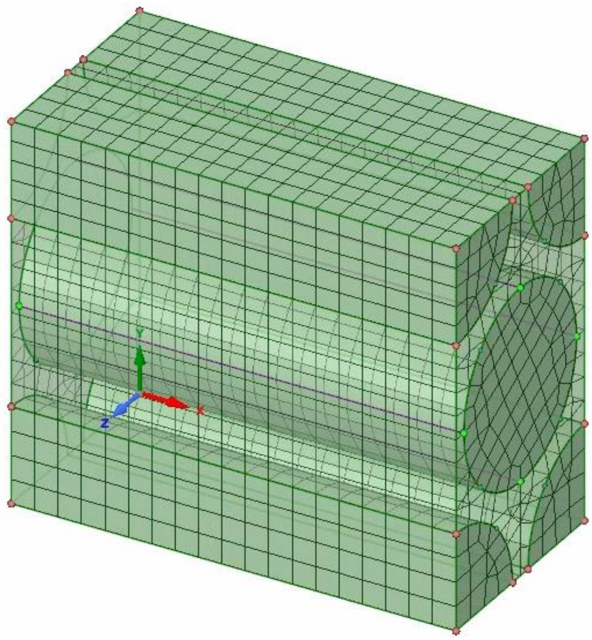


Figure 8 - Geometry and mesh for the composite modelling in Material Designer

Once the material parameters were set, the Material Designer application was solved. This gave the Young’s modulus, Poisson’s ratio, and Shear modulus in all directions and the density of the unique composite material created. This material was then used to create a layup for the wind turbine blade, explained in subsection 5.3.

5.3 Composite Layup

The ACP (ANSYS Composite PrePost) application was used to create the composite layup. It is specifically designed for composite materials and allows complete control over its thickness, orientation, and layup.

The first stage of using ACP was to create the composite fabric. For each model, the unique composite material created in Material Designer was used. The fabric was 0.2 mm thick because this is typical of prepreg composite fabrics [88]. The next step was to make the composite layup or "stackup". The stackup was defined as four layers of the fabric created in the previous step. They had the orientation of 0°, +30°, -30° and 0° and which were repeated ten times to create an 8 mm thick stackup. These orientations were used as they are recognised as a layup for producing turbine blades with good performance [89].

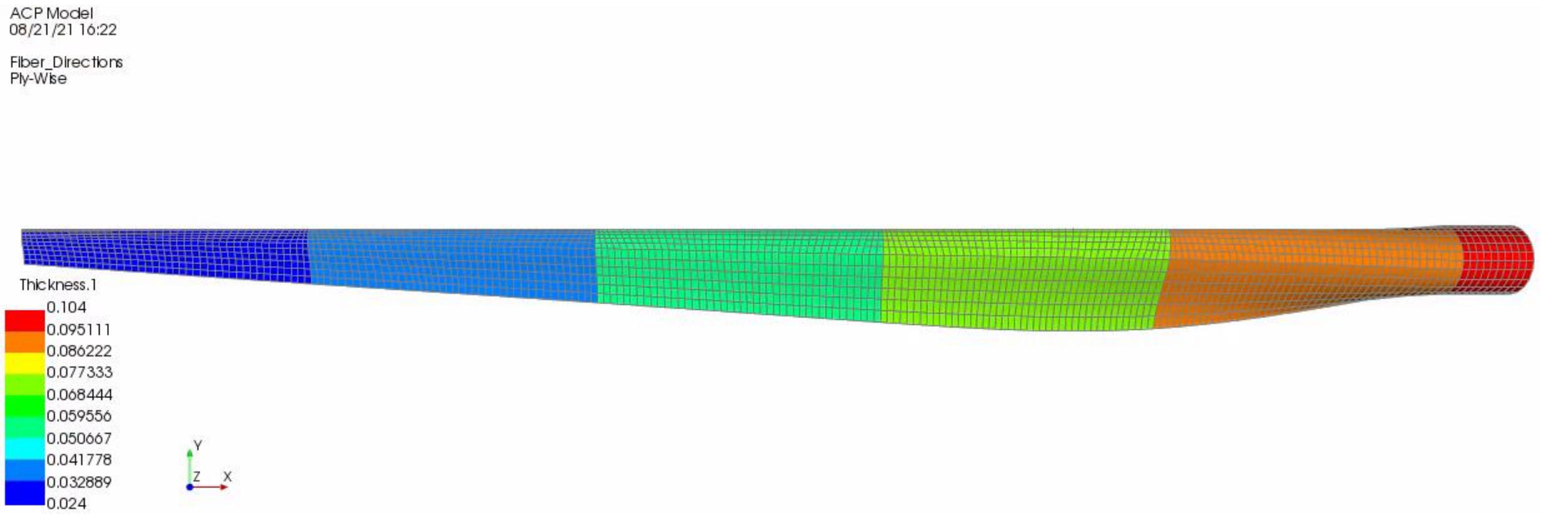


Figure 9 - Material thicknesses for the top turbine blade surface

Once the material stackup was defined, a rosette had to be created. The rosettes are used to define the coordinates of each surface. Two rosettes were created for this model, for the blade surface and the spar. Both rosettes defined the x or 0° direction as running along the turbine blade from the root to the tip.

Wind turbine blades have variable thickness, with the root being the thickest point and gradually thinning towards the tip. To simulate this, the model "geometrical selection rules" were set up. The blade surface was split into six sections and the spar was split into five sections, with each section given its own rule to allow for variable thicknesses. Each geometrical selection rule then required an "orientation selection" where the relevant rosette was selected and the direction of the stackup was set. For the blade surface, the stackups were layered from the top down. Therefore, there would be a smooth outer surface so the aerodynamics of the blade would not be affected.

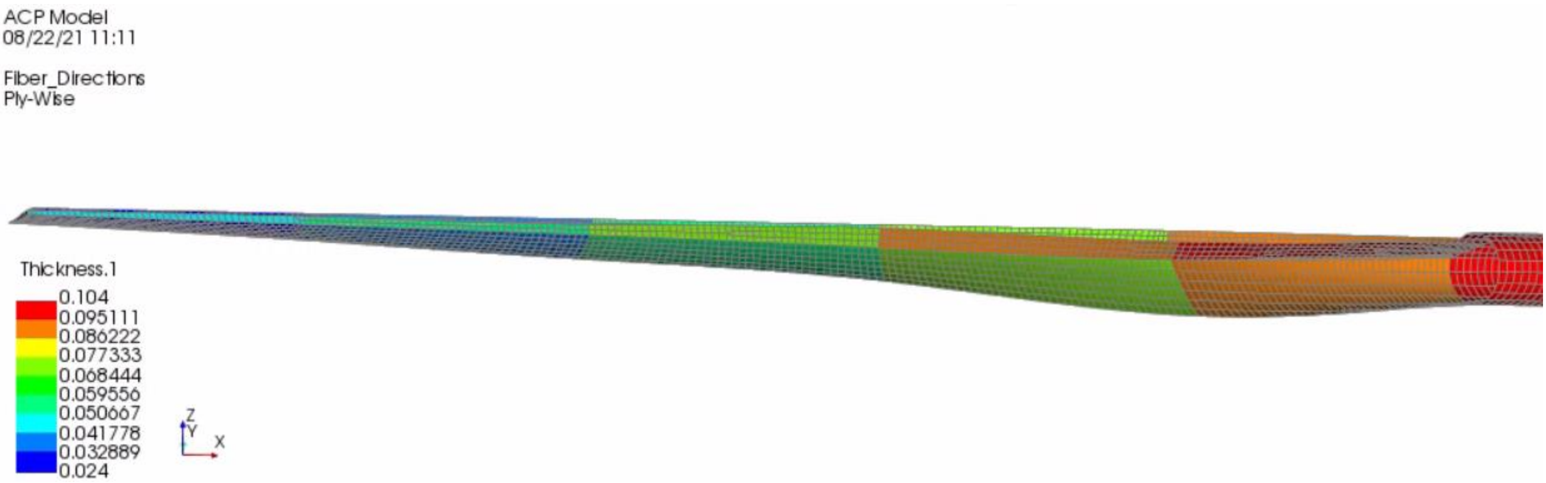


Figure 10 – Material thicknesses for the spar and the bottom turbine blade surface

The final stage of the composite layup was to create "modelling groups". A modelling group allows the number of stackup layers to be set for each of the geometry selection rules. Figure 9 shows that the thickness of the composite material on the top surface of the turbine blade is at its thickest point (0.104 m, 13 layers of the stackup) at the root and the thinnest at the blade tip (0.024 m, three layers of the stack up). Figure 10 shows how the bottom surface of the turbine blade has the same material thickness as the top surface. The spar thickness is also 0.104 m at the thickest point but is thicker than the turbine blade surfaces that surround it as the spar is designed to provide stiffness to the turbine blade. The thinnest section of the spar is 0.048 m thick, which is six layers of the layup. After the modelling groups for each section were set for the layup and the ACP part of the model creation was complete.

5.4 Load Cases

In this section, the load cases for the modelling will be set out. Two primary loads act on the wind turbine blade. The first is the aerodynamic load from the air passing over the wind turbine blade, which is described above in subsection 5.4.1; the second is the mechanical load caused by the mass of the materials described in subsection 5.4.2.

5.4.1 Aerodynamic load

The aerodynamic load was modelled for the wind turbine blade using Fluent. Fluent is an ANSYS application that can perform CFD (Computational Fluid Dynamics) modelling. The pressure profile across the turbine blade surface is calculated from the continuity and Navier-Stokes equations shown in Equation 1 and 2 respectively. The inputs into these equations are wind speed and rotation velocity of the wind turbine blade, and they are calculated for every element in the created mesh. In the study, it will be assumed that the blade is rotating at 2.22 rad/s, calculated from a wind speed of 12 m/s, a typical rated wind speed for 2.0 MW HAWT [90]. As this project is focused on material comparison between composite materials, the wind speed is set to the rated wind speed. To understand the damage and maximum deformation, the wind speed would need to be set to a higher value to model more extreme loading conditions; this was beyond the scope of this investigation.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho v_r = 0 \qquad (1)$$

$$\nabla \cdot (\rho \vec{v_r} \vec{v_r}) + \rho(2\vec{\omega} \times \vec{v_r} + \vec{\omega} \times \vec{\omega} \times \vec{r}) = -\nabla p + \nabla \cdot \bar{\bar{\tau}}_r \qquad (2)$$

To calculate the pressure on the surface of the turbine blade, a control domain had to be created. Figure 6 and Figure 7 show the domain area designed to represent a third of the full wind turbine domain. A mesh was created, which is described in subsection 5.6.1, to discretise the calculation into elements.

The boundary condition used for the model was that the wind's velocity is 12 m/s with a turbulent intensity of 5% and turbulent viscosity rate of 10%. This means that the air flow is laminar as it reaches the turbine blade. The outlet pressure was set to 1 atm and there was no slip across the blade surface. The domain edges were modelled as periodic boundaries, which ensured they acted as one-third of a complete wind turbine domain. The fluid was set to air at 15°C, which has a density of 1.225 kg/m^3 and a viscosity of 1.7894x10^5 kg/ms.

The simulation was set to be steady-state and used the pressure-based solver. The pressure-based solver was used because the fluid is travelling at a low speed and is incompressible. The k-omega SST (Shear Stress Transport) model was used for the viscous settings with all other settings kept as default. The frame motion was selected for the fluid with -2.22 rad/s rotation about the z-axis to simulate the turbine blade rotation.

After running the model to converge the residuals to 1x10^{-6}, the resulting pressure on the blade's surface is shown in Figure 11 and Figure 12. The areas of highest pressure are along the leading edge of the top of the turbine blade surface. The pressure increases towards the tip of the blade due to the geometry of the blade. This is desirable as it creates a larger moment reaction as it is the furthest point from where the blade is fixed at the root. The lowest pressure is on the bottom of the turbine blade surface near the leading edge and near the tip. This verifies that the movement of the wind turbine blade is from high to low pressure which is in the negative z-direction.

This concluded the use of the Fluent application in ANSYS. To introduce the mechanical loading into the modelling the Static Structural application was used. This is described in subsection 5.4.2.

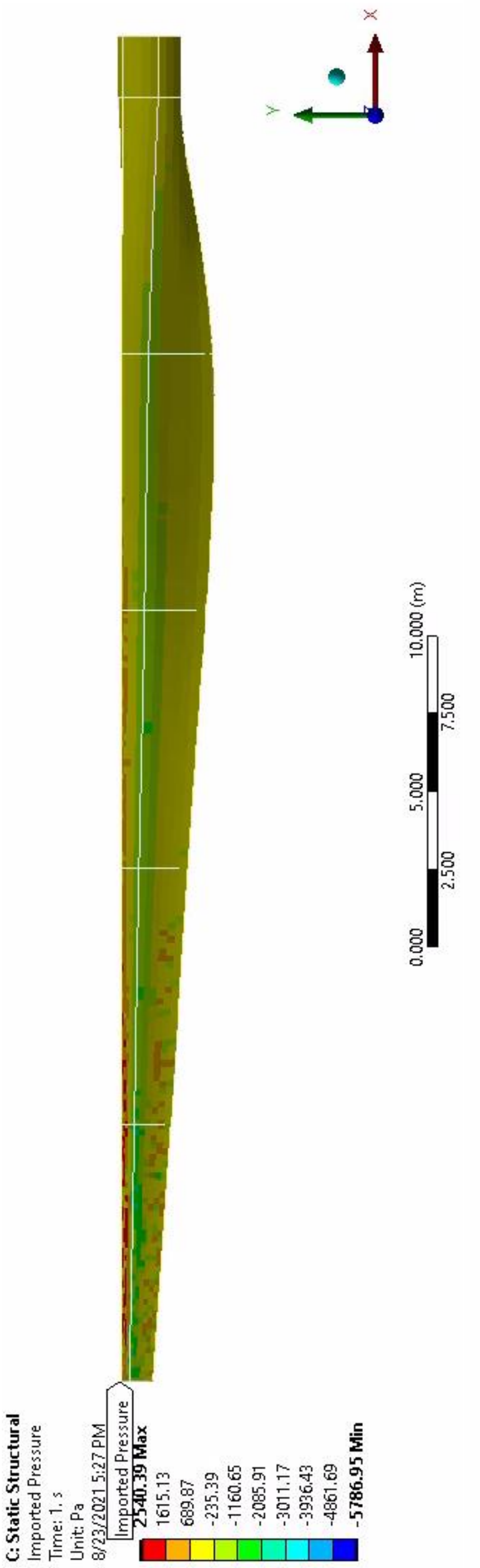


Figure 12 – Aerodynamic pressure acting on the top surface of the wind turbine blade

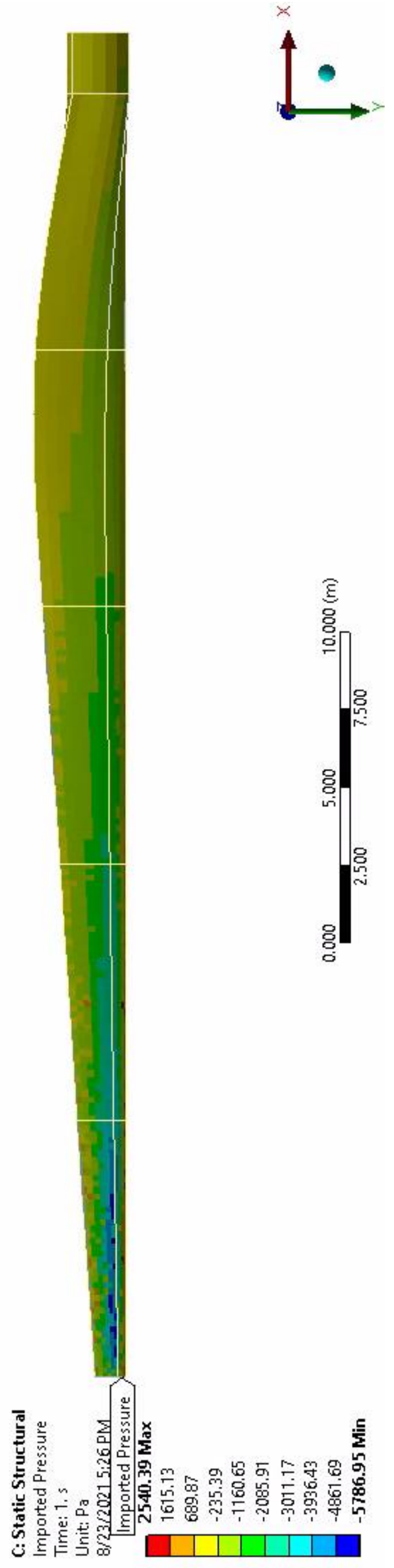


Figure 11 - Aerodynamic pressure acting on the bottom surface of the wind turbine blade

5.4.2 Mechanical load

The mechanical load on the turbine is made up of two sources. The largest is the root radial force from the rotation of the turbine blade, which is shown in Equation 3. It shows the force acting on the blade which is dependent on the speed it is rotating. As the rotational velocity is squared, the force increases exponentially. To determine the mechanical load the rotation speed had to be set. As the wind speed was assumed to be 12 m/s, the rotation speed of the wind turbine blade was calculated to be -2.22 rad/s in the z-direction which had to be set as a rotational velocity in Static Structural application.

$$F_r = -mr\omega^2 \tag{3}$$

The second mechanical load acting on the blade is from the mass of the blade itself. This is automatically considered when the model is set up. To simulate the interaction with the turbine blade hub a remote point was created which fixed the edges of the turbine blade root to an imaginary point at the centre of the circle the edges create. This point is also the origin of the model. This meant that the root is completely fixed and creates a moment reaction about the origin.

5.5 Turbine Blade Material Assumptions

When creating the model some assumptions and simplifications had to be made. The first is that the materials used are perfect and without any defects which could occur from manufacturing or transport. Another assumption is that the materials used will all have the properties found in literature. Particularly for the natural fibres and PLA, the properties might vary and so the results produced in this project will only be valid for materials used which have comparable properties.

There are also multiple assumptions made for the composite materials. The first is that the bonding is assumed to be perfect which is pertinent with the use of less mature materials such as natural fibres where the fibre volume fractions and layup process is not well understood. This could be investigated by conducting physical testing, but this could not be conducted in this project owing to lack of access to laboratory facilities.

Another material assumption is that the natural fibres are continuous. This is due to the way the Material Designer application works where a small section of material is modelled and then extrapolated out across the whole material. In practice the fibre lengths, particularly for the shorter natural fibres would cause the composite material to be less stiff.

As explained in subsection 2.2.2 (page 9) natural fibre composites will absorb moisture from the environment, and this can degrade the mechanical properties of the fibres. However, for the purposes of this study it was assumed that there is no additional moisture absorption in the natural fibres used. If natural fibres are to be used in wind turbine blades, this aspect of their performance will need to be investigated.

5.6 Mesh Generation

To discretise the numerical solution a mesh was designed with the aim of being uniform across the turbine blade and spar geometry. Three meshes were created during the investigation for Fluent, Material Designer and ACP. The mesh created in Fluent for the fluid domain around the turbine is explained in 5.6.1. The mesh that was created in Material Designer was described in subsection 5.2 because it was a simple mesh. The mesh that was created in ACP for the composite material modelled is described in subsection 5.6.2.

5.6.1 Fluent

The first was to mesh the control domain around the turbine blade in Fluent to calculate the aerodynamic pressure acting on the blade. This was created using tetrahedral elements which are automatically used for CFD meshes.

The mesh shown in Figure 13 shows how there is a high concentration around the outside of the turbine blade surface. This was to ensure that there is detailed modelling where the fluid flow is most complex. The method for designing this mesh is explained below.

The advanced size function was set to edges and curves to improve the mesh around the wind turbine blade surface. The relevance centre was set to medium to reduce the size of the elements.

Match control was inserted to set the periodic boundary between the two inside faces of the fluid domain. This tells Fluent that the either side of the boundary is the same thing which is simulating what it would be like with three turbine blades.

Mesh sizing was used to define the element size around the blade to 0.3 m and the behaviour was set to hard to ensure that the sizing was valid in all elements. An inflation layer was created to capture the boundary layers that will occur around the blade surface as this is the area where the fluid flow will be complex. The elements in the inflation layer are hexahedral.

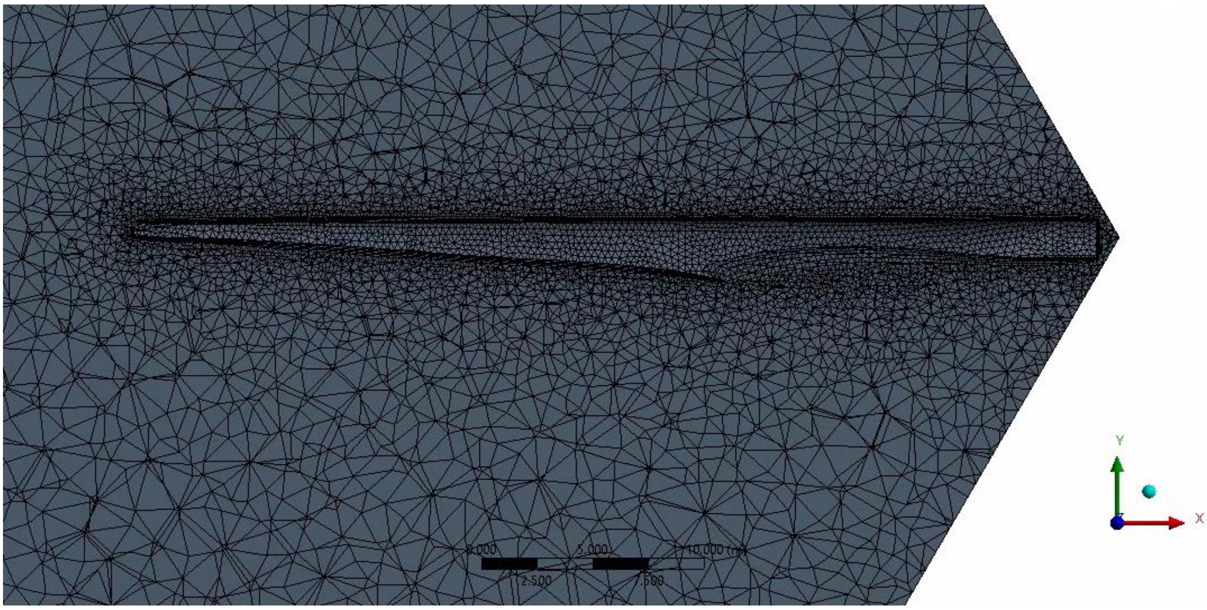


Figure 13 - Mesh created for the Fluent model of fluid passing over the turbine blade

A 30 m sphere of influence was added which used the centre of the blade as the centre of the sphere. The sphere was set to have a maximum element size of 2 m, so creating further refinement in the area around the turbine blade surface.

5.6.2 ANSYS Composite PrePost (ACP)

The final mesh that was created was within ANSYS ACP was used. The mesh was setup to be composed of hexahedral and the size of the mesh was controlled by the face sizing functions and is shown in Figure 14. The size of the elements in the mesh were set to be 0.2 m as this split the geometry up effectively and produced good mesh evaluation results which are shown in subsection 5.7.4. This was applied across the whole turbine blade geometry. The same mesh for the full turbine blade was used in Fluent, ACP and Static Structural applications of ANSYS.

To increase the level of control over the turbine blade surface the face meshing function was used. The face meshing function maps a structured mesh on the face of the object to improve the mesh quality. The face meshing function was not required for the spar as it is a relatively uniform geometry where a simple mesh will be sufficient to achieve accurate results.

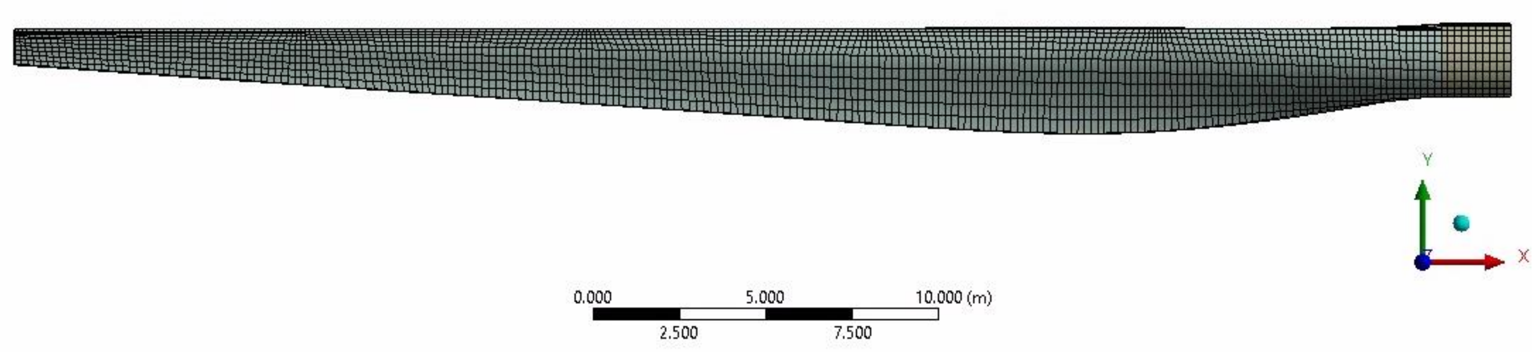


Figure 14 - Mesh for the turbine blade geometry

P Knupp [91] explains that it is important to have a good quality mesh to achieve a fast rate of convergence, increase the solution accuracy and reduce the computing time needed. The quality of a mesh can be quantified in numerous ways, which are discussed in subsection 5.7.

5.7 Mesh Evaluation

Metrics such as aspect ratio, skewness, and orthogonal quality were used to evaluate the meshes created. These metrics were used to help produce a good quality mesh and were monitored whilst producing the mesh. The desirable values for these metrics can be found in literature. The aspect ratio is explained in subsection 5.7.1, subsection 5.7.2 explains the skewness metric and subsection 5.7.3 explains the orthogonal quality.

5.7.1 Aspect ratio

The aspect ratio of the mesh elements is the ratio between the longest and shortest edge length, indicating how stretched a cell is. A ratio of 1 is the ideal value although this is not achievable for complex geometries. An aspect ratio of <5:1 is desirable as specified in the Fluent user guidebook [92].

5.7.2 Skewness

The skewness metric is calculated from the angles of the corners of each element. The angle is compared with the angles of an equilateral equivalent of the shape. Ideally, a hexahedral mesh would have angles of 90° which would give a skewness of 0.

In the Fluent user guidebook, the maximum value is recommended to be below 0.95 and the average below 0.33 [92]. Values above 0.95 can cause convergence difficulties.

5.7.3 Orthogonal Quality

The orthogonal quality is similar to skewness but is a metric of how orthogonal the elements are compared to elements around it. This is done by comparing the face normal vector to the vector from each cell centroid to each face [93]. The orthogonal quality of an element is better as it gets closer to one.

5.7.4 Mesh Quality Metric Results

Table 3 shows the mesh quality metrics for the meshes created for the fluid domain in Fluent and for the turbine blade in ACP. As the mesh created in Material Designer has few options to customise the mesh there are no mesh quality metrics available.

Table 3 - Mesh quality metrics for two meshes created

Geometry		Aspect Ratio	Skewness	Orthogonal Quality	Number of Elements
Fluid Domain	Minimum	1.164	0.001	0.026	369312
	Maximum	46.722	0.974	0.992	
	Average	2.395	0.236	0.733	
Turbine Blade	Minimum	1.000	0.000	0.335	5241
	Maximum	5.933	0.736	1.000	
	Average	1.596	0.080	0.986	

The results show that the average aspect ratios of both meshes are well below the maximum acceptable ratio of 5:1. However, they both have a maximum ratio above 5:1, although the maximum for the turbine blade is 5.9:1, which is not worrying. The maximum ratio for the fluid domain of 46.7:1 is very high. However, the mesh is acceptable as this is only the case for an extremely low number of elements.

The skewness of the fluid domain mesh has a slightly high maximum although the mesh is acceptable as the average is well below the maximum acceptable range. Similarly, to the aspect ratio, the number of elements above 0.95 is minimal, so the mesh is acceptable. The turbine blade mesh skewness values are all below 0.95 and the average is well below 0.33, showing that this mesh is good when considering this metric

The orthogonal quality of the fluid domain mesh is good due to the average being close to one. The minimum is low, but as it is not low for many elements, the mesh is acceptable. The average is very high for the turbine blade mesh, and the minimum is also acceptable, showing that this mesh is good.

5.8 Useful Laboratory Work

Due to constraints on the project such as COVID-19, time and costs, laboratory work has not been possible. This has limited the validity and accuracy of the project's findings. The work that could have been done in the laboratory includes physically testing of natural fibres and composite materials to determine their mechanical properties. This would have been beneficial as there is limited research data on some of the properties required in the modelling of composite materials in the Material Designer function of ANSYS.

Producing composite materials using the fibres and matrix materials chosen for the modelling would have been advantageous to validate the results of the material modelling done using the Material Designer function in ANSYS and properties found in research data. A hand layup method would have been used to produce the composite materials as this is cost-effective and easy to set up for low-volume composite materials. The fibres fabrics and matrix materials would be purchased from an outside source such as from Composites Evolution (Chesterfield, UK). They supply natural fibre prepregs which can be used in the same way as glass fibre prepregs in hand layup manufacturing techniques. As PP is more viscous than epoxy and PLA before being cured other manufacturing techniques such as injection moulding could have been explored.

The properties that were difficult to establish from the literature for the natural fibres were Young's modulus in the Y and Z direction, Poisson's ratios and Shear modulus in the YZ and XZ direction. Experiments to determine these could be used to validate the assumptions in the modelling. To determine the maximum tensile load carrying capacity and the Young's modulus a tensile test could have been conducted. This test would have been carried out to ASTM (American Society for Testing and Materials) D3039/D3039M test procedure [94]. A three-point bending test could have been conducted to investigate the flexural strength, maximum load at failure and the flexural modulus of the composite materials. This test would follow the ASTM D5023 standard test procedure [95]. Another useful test that could have been conducted is an impact Charpy test which would give the impact strength of the composite material. This would follow the ASTM D1822 standard test procedure [96].

To determine the quality of the composite materials tests such as CT scanning or cross section microscopy could be conducted to investigate how the fibres align in the composite material as well as estimating the fibre volume fractions. For glass fibre composites a resin burn off test could be carried out to assess the weight of the fibres that remain. Finding out the fibre volume fraction is more difficult for the natural fibres as they would not survive a resin burn off test. They could be investigated by microscopy although this would require long preparation time and would need to be done across multiple parts of the composite to gain and average [97].

Another test that could have been conducted is the soil burial test which can be used to investigate the biodegradability of the materials [98]. This would be conducted on the PLA natural fibre composites.

6.0 Results

This section presents the results from the modelling and considers their validity. The composite material properties found from the Material Designer application and how they compare to each other is described in subsection 6.1. Subsection 6.2 reports the results from the full wind turbine blade and compares the performances. Subsection 6.3 provides results from a case study of using more material for the natural fibres composites to investigate whether this reproduces comparable stiffness to the glass fibre composites.

6.1 Composite Material Properties

This section shows the results from the Material Designer function in ANSYS 20.0 using the materials described in section 4.0 (page 14).

Table 4 shows the mechanical material properties for each of the composite materials modelled. It shows how the composites with glass fibre reinforcement have the highest Young's modulus, followed by the hemp composite and the flax composites have the lowest. This is an expected result from the mechanical properties of the fibres and matrix materials shown in Table 1 and Table 2 (page 14 and 17). The Young's modulus is significantly higher in the x-direction of all the composite materials. This shows the anisotropic characteristics that allows the composite to be laid up in the most effective orientation for the required function.

Table 4 – Mechanical properties of each composite material using each fibre and each matrix material

Material		Young's Modulus (GPa)			Poisson's Ratio			Shear Modulus (GPa)			Density
Fibre	Matrix	X Direction	Y Direction	Z Direction	XY	YZ	XZ	XY	YZ	XZ	(kg m^{-3})
Glass	Epoxy	52.25	17.60	17.60	0.25	0.25	0.36	6.43	6.46	6.43	2168
	PP	51.47	6.86	6.86	0.25	0.25	0.39	2.36	2.47	2.36	2090
	PLA	51.49	7.27	7.27	0.25	0.25	0.39	2.51	2.61	2.51	2120
Hemp	Epoxy	39.92	12.68	12.68	0.29	0.29	0.40	4.67	4.53	4.67	1364
	PP	38.88	4.71	4.71	0.29	0.29	0.44	1.67	1.64	1.67	1260
	PLA	38.92	5.00	5.00	0.29	0.29	0.44	1.77	1.74	1.77	1412
Flax	Epoxy	33.62	12.24	12.24	0.29	0.29	0.40	4.52	4.39	4.52	1364
	PP	32.58	4.64	4.64	0.29	0.29	0.43	1.65	1.62	1.65	1260
	PLA	32.62	4.93	4.93	0.29	0.29	0.43	1.75	1.72	1.75	1412

The shear modulus is highly dependent on the matrix material. The composites with the epoxy matrices have the highest shear modulus with the PP and PLA showing similar values. The epoxy values are approximately two thirds higher than that of the PP and PLA composites. The shear modulus of the glass fibre composites is approximately a quarter higher than the natural fibre composites. Both of these are consistent with the material properties in Table 1 and Table 2 (page 14 and 17) which gives confidence that the modelling has been completed correctly.

6.2 Wind Turbine Blade Testing

The focus of this investigation was to compare how the wind turbine blade performs when made of the different composite materials under typical wind conditions. The key results from the investigation are shown in Table 5. The results and are discussed further in the following subsections. Subsection 6.2.1 discusses the mass of the turbine blades. Subsection 6.2.2 discusses the maximum deformation results and analyses the max deformation against the mass of each blade. Subsection 6.2.3 discusses the equivalent stress and what this means. Subsections 6.2.4.1 and 6.2.4.2 then report where the maximum principal stress and strain exist on the turbine blade and how this could affect the blade's performance.

Table 5 – Key results from the full turbine simulations using the different composite materials

Material		Mass (kg)	Max deformation (m)	Equivalent von Mises Stress (MPa)		Max Principal Elastic Strain (m/m)	Max Principal Stress (MPa)
Fibre	Resin			Max	Average		
Glass	Epoxy	34082	1.2211	38.892	4.9805	0.0010992	37.775
	PP	32856	1.6282	50.462	4.266	0.0021323	47.596
	PLA	33327	1.5948	50.041	4.3144	0.0020488	47.261
Hemp	Epoxy	21443	1.7325	34.369	4.5034	0.0012891	33.403
	PP	19808	2.4626	43.974	3.5268	0.0024233	41.470
	PLA	22197	2.2585	43.695	3.5591	0.0023809	41.266
Flax	Epoxy	21443	1.7728	31.192	4.3363	0.0013452	30.468
	PP	19808	2.4914	40.069	3.3867	0.0024465	37.931
	PLA	22197	2.2820	39.764	3.4281	0.0024055	37.701

6.2.1 Mass of the Turbine Blades

The mass of each turbine blade is shown in Table 5. Due to the lower density of the natural fibres compared to the density of the glass fibres, the natural fibre blades are approximately a third lighter. This is a positive attribute for a wind turbine blade as it means that less aerodynamic pressure is required to rotate the blade and so more energy can be produced. As the density of the hemp and flax fibres were identical, so too was the mass of the turbine blades made from these materials. Another factor which causes the wind turbine blades which used natural fibres to be lighter than the glass fibre blade is that the fibre volume fraction is smaller. This means there is a higher percentage of resin in the natural fibre composite turbine blades which is a less dense than all the fibres.

There is a relatively small difference between the resin densities which suggests that this would have little effect on the performance of the wind turbine blade.

6.2.2 Maximum Deformation of the Turbine Blades

The maximum values for the deformation of the wind turbine are reported in Table 5. The turbine blade with the largest maximum deformation (2.491 m) was the blade which used flax fibres with a PP matrix. This is a large deformation although due to the relatively low stiffness that flax and PP have and the large turbine blade (42 m) this can be expected. The modelling results in Figure 16 and Figure 17 show the deformation which is predominantly in the negative z-direction, although there is also some in the y-direction. The maximum deformation is at the tip of the blade which is expected as the root is fixed. This gives confidence in the modelling as this is the direction where the aerodynamic pressure is acting, and the turbine blade is rotating.

The smallest value of maximum deformation (1.221 m) is for the turbine blade which uses glass fibres and an epoxy matrix. This is expected as this material showed the highest Young's modulus in the material modelling results Figure 19 and Figure 18 show that the deformation is in the same direction as the flax-PP composite. However, the maximum deformation is approximately half of the deformation in the flax-PP turbine blade. This is significant because the deformation can affect how the turbine blade performs and can cause other issues during operation, such as striking other components of the wind turbine.

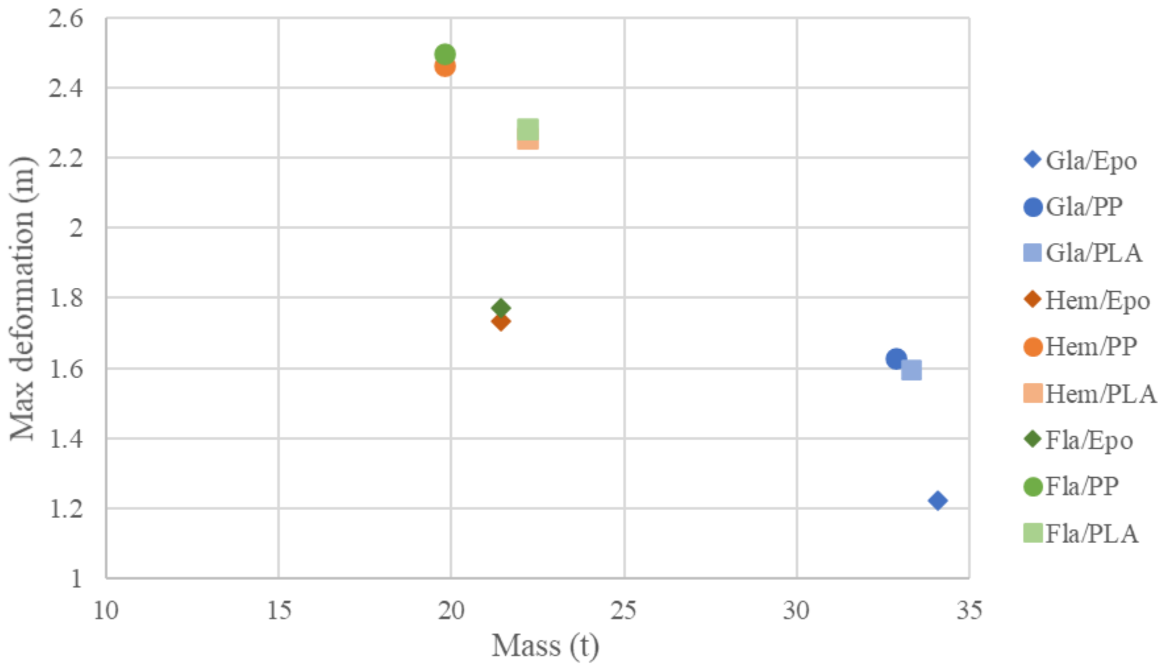


Figure 15 - Plot of maximum deformation against mass for all the turbine blades modelled

Figure 15 shows a plot of the maximum deformation against the mass of the turbine blades. All the glass fibre turbine blades are grouped in the bottom right-hand corner which shows that the maximum deformation is smaller, but the mass of the blade is larger. The turbine blades with natural fibres have a larger deformation and there is more fluctuation in their masses due to the higher percentage of resin in the composite material compared to the glass fibre turbine blades.

This plot demonstrates that there is a trade-off between the mass of the turbine blade and the maximum deflection. It is advantageous to have a low mass turbine blade because it easily overcomes friction and begins to rotate with a low cut in wind speed. However, the acceptable values for deformation would have to be explored to understand whether the turbine blades that use natural fibres are acceptable.

Further investigation into the maximum deformations when extra material is added to a wind turbine blade using natural fibres is discussed in subsection 6.3.

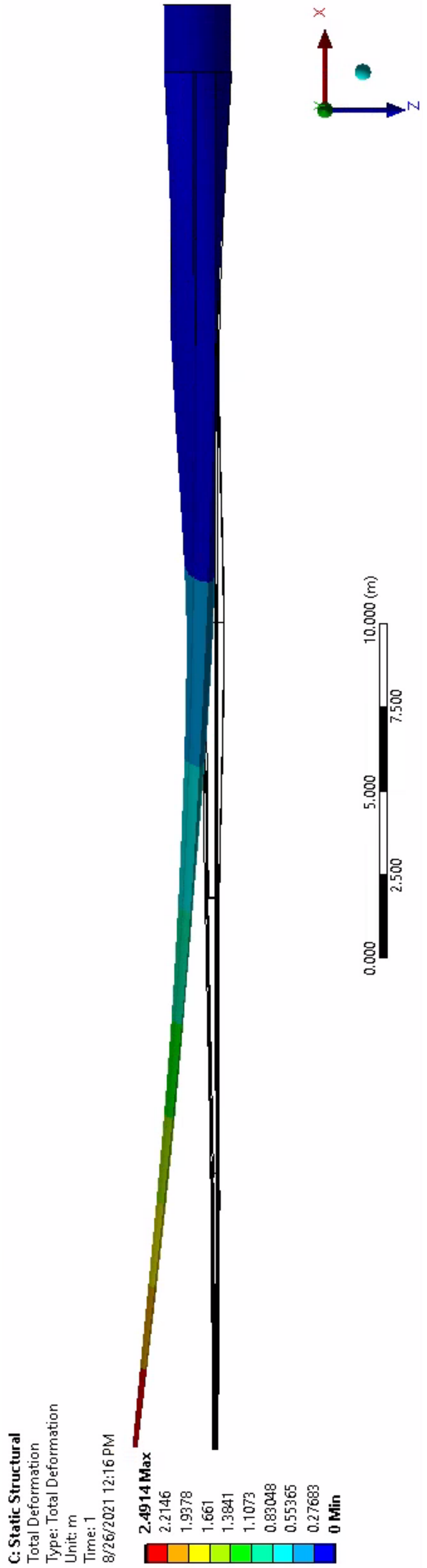


Figure 16 - Side view of the deformation of the flax/PP turbine blade

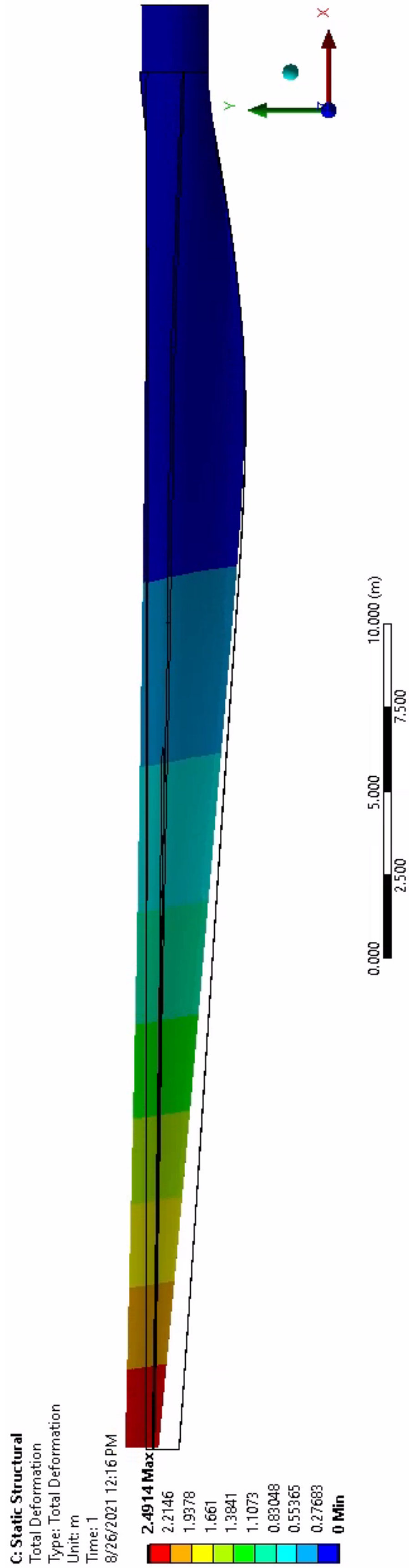


Figure 17 - Top view of the deformation of the flax/PP turbine blade

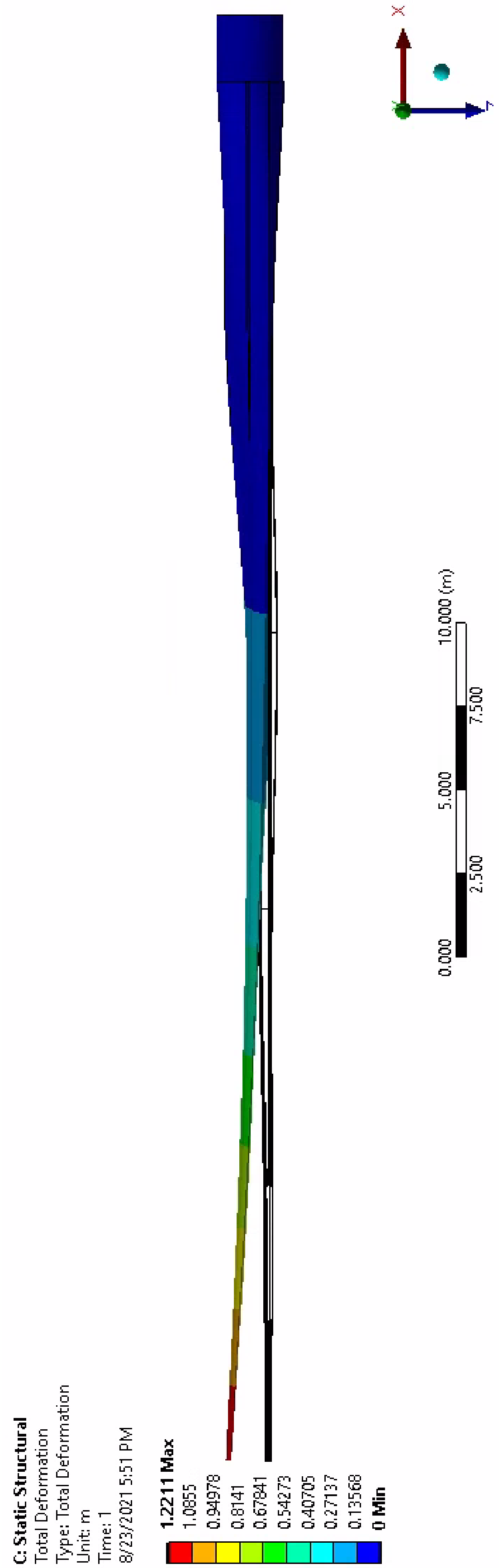


Figure 18 - Top view of the deformation of the glass/epoxy turbine blade

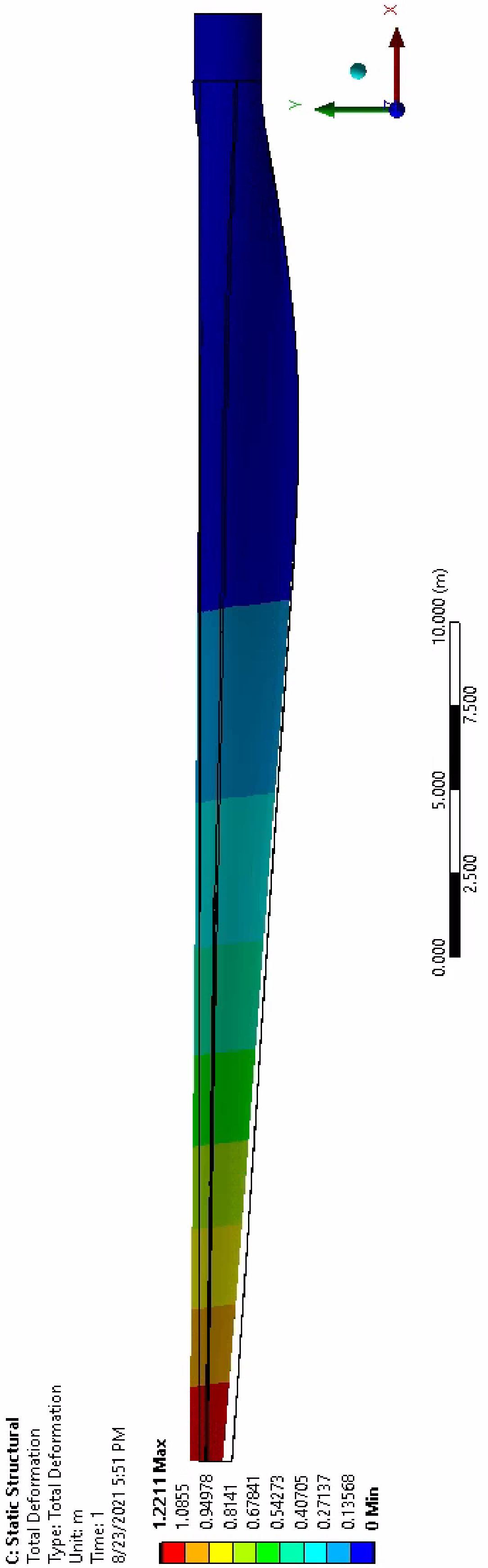


Figure 19 - Side view of the deformation of the glass/epoxy turbine blade

6.2.3 Equivalent Stress

The von Mises equivalent stress is a multi-axial yield criterion which considers the stress state in all direction. This means that it can give a more accurate value of the total stress the material is under. The value of equivalent stress can then be compared to the yield strength of a material to understand whether a material will fail. It is a useful indicator of the safety of a component as it indicates how much stress the material is under.

The investigation found that the turbine blade with the largest maximum von Mises equivalent stress is the glass fibre and PP matrix turbine blade. The maximum equivalent von Mises stress for the glass PP turbine blade is 50.46 MPa compared to 37.78 MPa for the glass fibre and epoxy resin material. This is approximately 25% higher which is a significant increase. However, as this investigation is using the loading at the rated wind speed, this figure is still relatively low when compared to the material properties.

The yield strength of the materials was not found in this investigation due to time constraints so a true indication of whether the material will fail is not possible. In future investigations, the yield strength of the material and the maximum equivalent von Mises stress in extreme conditions would need to be investigated to understand whether the turbine blade would fail.

The location of the highest stress point, shown in Figure 20 and Figure 21, is a point approximately a quarter of the blade away from the root where the spar and the turbine blade surface meet, on the top surface. There is also high stress across the span of the interface between the spar and the turbine blade surface. The reason for high stress in this area is due to material being constrained in this area spar.

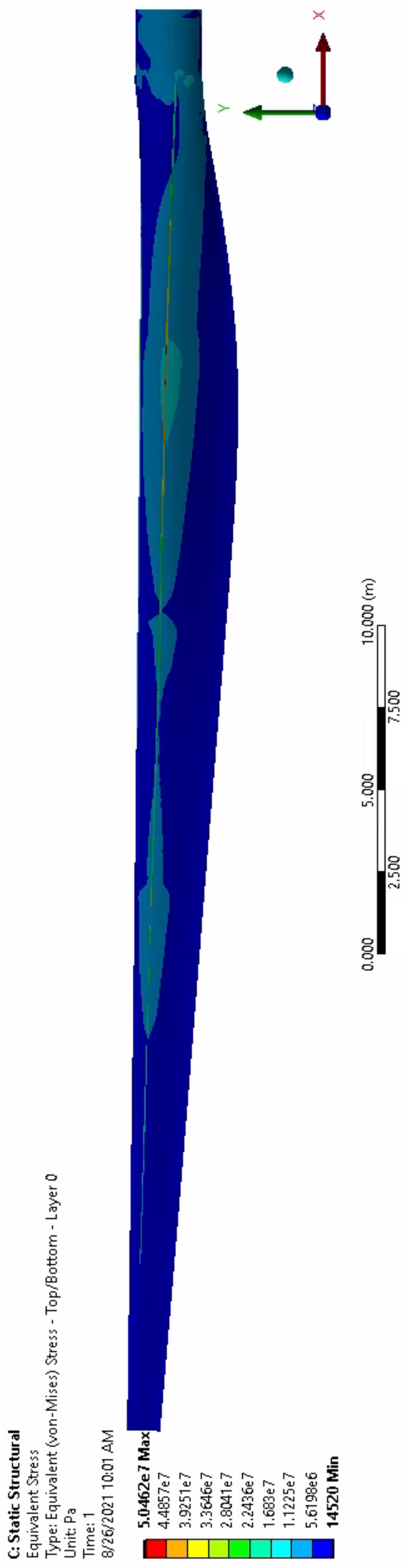


Figure 20 - Principal stress for the glass fibre and epoxy matrix turbine

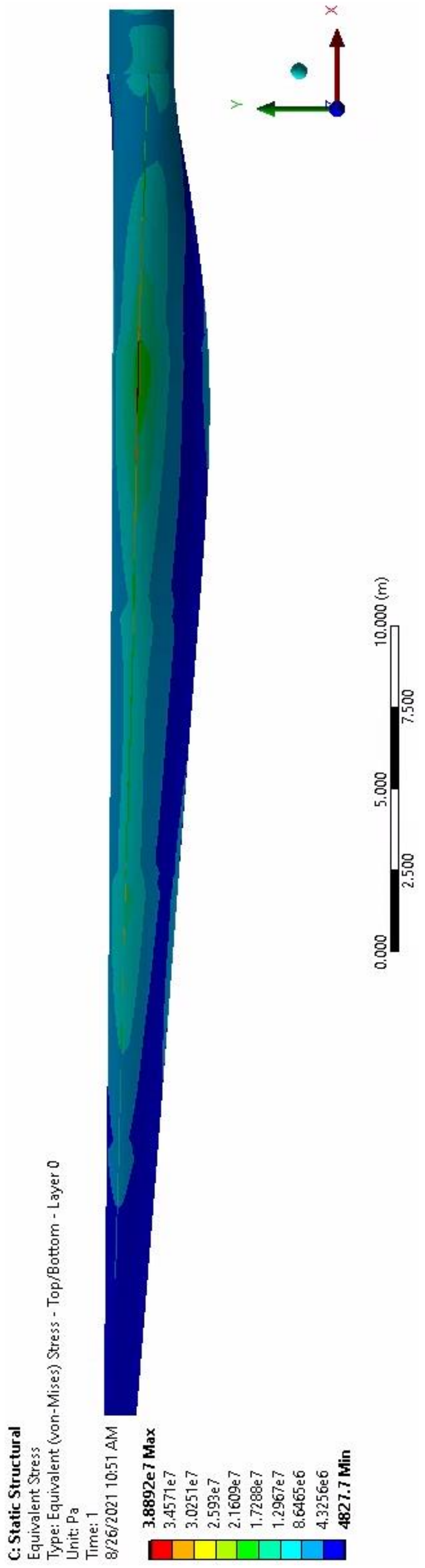


Figure 21 - Principal stress for the glass fibre and PP matrix turbine blade

6.2.4 Maximum Principal Stress and Strain

The maximum principal stress and strain on the turbine blade can also be used as a metric to compare the performance. Conversely to the equivalent von Mises stress, the principal stress is the stress that acts in one direction on a certain point of the turbine blade. Stress is the normal force applied onto an area. The principal strain is the deformation that an area is experiencing due to stress.

Figure 22 shows the comparison of the turbine blades' maximum principal stress and strain. There is clear correlation that the values are dependent on the matrix material as the epoxy matrix turbine blades have the lowest values of stress and strain. The fibres also have an effect as the stiffer glass fibre turbine blades have higher stress but lowest strain. The flax fibre turbine blades are least stiff and have the lowest stress but the highest strain. This shows how it is trade-off between stress and strain and this would need to be considered during the next stage of investigation whether more sustainable materials could replace the current materials.

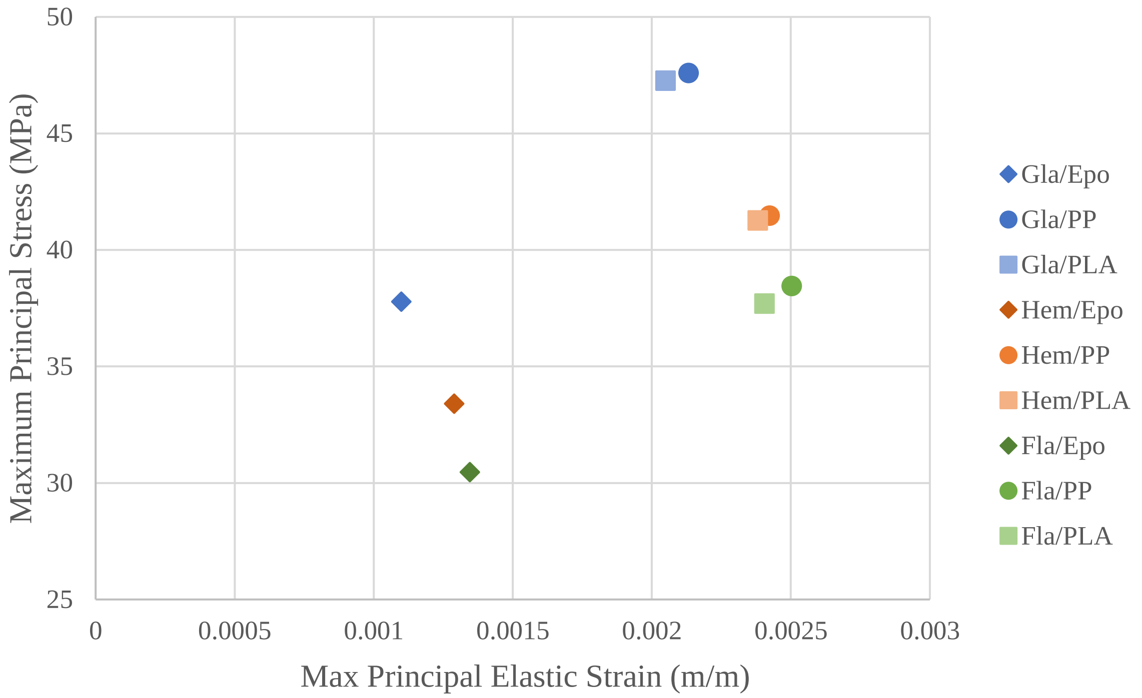


Figure 22 - Plot of maximum principal stress against maximum principal strain for all the turbine blades

The effect of the stress and strain on the turbines blades is discussed further in subsections 6.2.4.1 and 6.2.4.2.

6.2.4.1 Maximum Principal Stress

Figure 23 and Figure 24 show a representation of the location of the principal stress on the glass fibre and epoxy matrix, and glass fibre and PP matrix turbine blade. The turbine blade which has the highest maximum principal stress is the glass fibre and PP matrix blade and the glass fibre and epoxy matrix blade is used as a comparison. The maximum value is 47.596 MPa for the glass fibre and PP blade which is slightly higher than the 37.775 MPa for the glass fibre and epoxy blade. This is an increase of approximately 20%. The glass fibre turbine blades have the highest values of stress, when compared to the other blades, for all the matrix materials showing that the stress is highly dependent on the stiffness of the material. As the natural fibre materials are less stiff, they experience lower values of stress which can be a positive for limiting materials degradation or damage. However, this leads to higher values of strain which is explored in the next subsection.

Similarly, the maximum principal stress on the turbine blade is concentrated at a point approximately a quarter of the blade away from the root where the spar and the turbine blade surface meet, on the top surface. The reason that this area has high levels of stress is due to the geometry of the turbine blade and the forces acting on it. As the blade is more constrained in the area where the spar is, this is causing the blade to pivot about this point. To reduce the stress the design of the blade could be optimised, or less stiff material could be used but that would cause larger deformation and strain.

Figure 24 and Figure 23 show that there is a defined line that has high stress along the length of the turbine blades. This is expected as the area where the turbine blade surface is more constrained due to the interface with the spar. However, on closer inspection of the results there may be an issue with the model with the spar protruding from the turbine surface. Due to time constraints on the project, it was not possible to investigate this further, but this would be considered in future work.

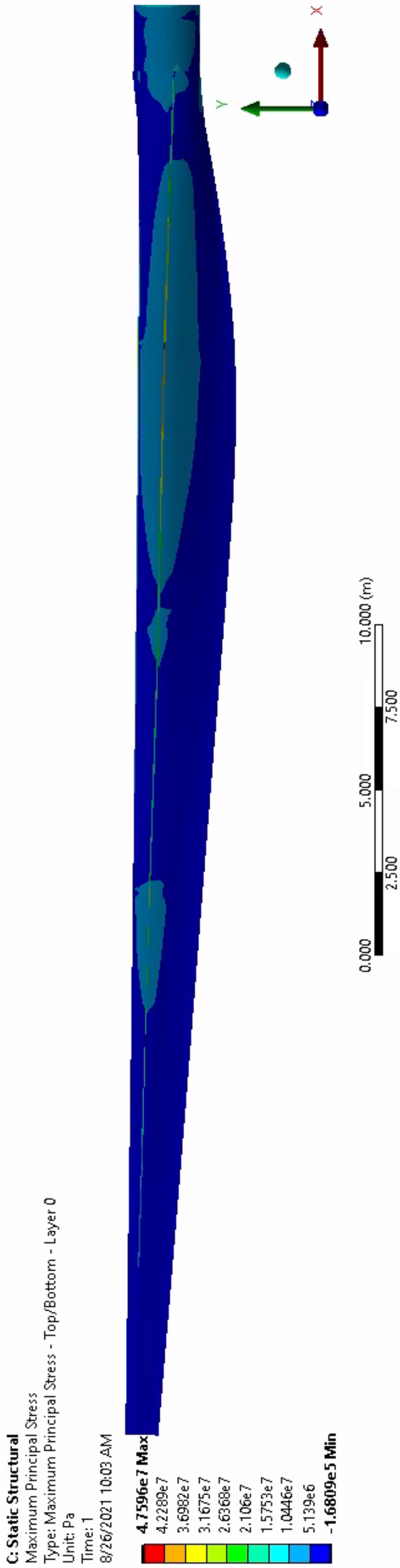


Figure 23 - Maximum principal stress for the glass/PP turbine blade

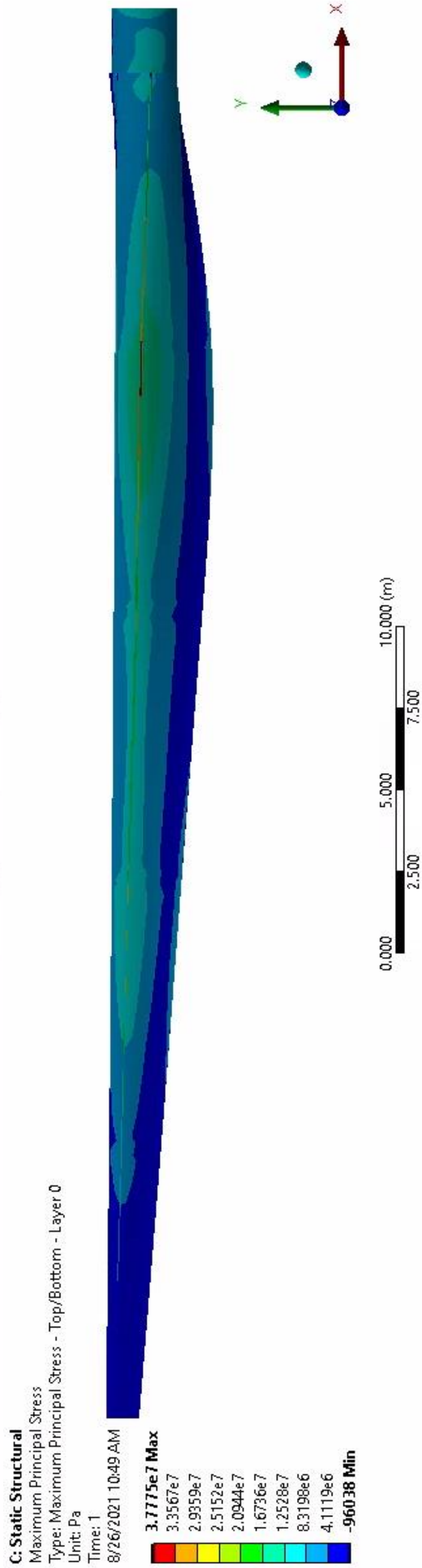


Figure 24 - Maximum principal stress for the glass/epoxy turbine blade

6.2.4.2 Maximum Principal Strain

Figure 24 and Figure 25 show a physical representation of location of the principal strain on the glass fibre and epoxy matrix, and flax fibre and PP matrix turbine blade. The turbine blade with the maximum value for principal strain is the flax and PP blade, and the glass fibre and epoxy blade is being used for a comparison. The maximum value of strain on the flax fibre and PP matrix blade is 0.002503 m/m compared to the 0.001099 m/m for the glass fibre and epoxy matrix blade. This is approximately 55% larger which is a significant increase. The strain is dependent on the stiffness and how much it deforms. This is expected from the material properties that were shown in Table 4. To reduce the strain a stiff material or additional supporting material could be used.

Figure 24 and Figure 25 show how the strain is primarily located around the same location as the stress. This is expected as this is where there is the maximum force and constraints that cause the material to deform. There is a larger spread of strain on the glass fibre and epoxy matrix material which is due to the stiffer material being able to dissipate the force more effectively. If flax fibre and PP matrix was used for further investigation, then work would need to be done to improve the stiffness of the blade. However, the flax fibres and PP matrix turbine blade is the worst performing so other sustainable material turbine blades such as natural fibre and epoxy matrix turbine blades could be used as their maximum strain is comparable to the glass fibre turbine blade.

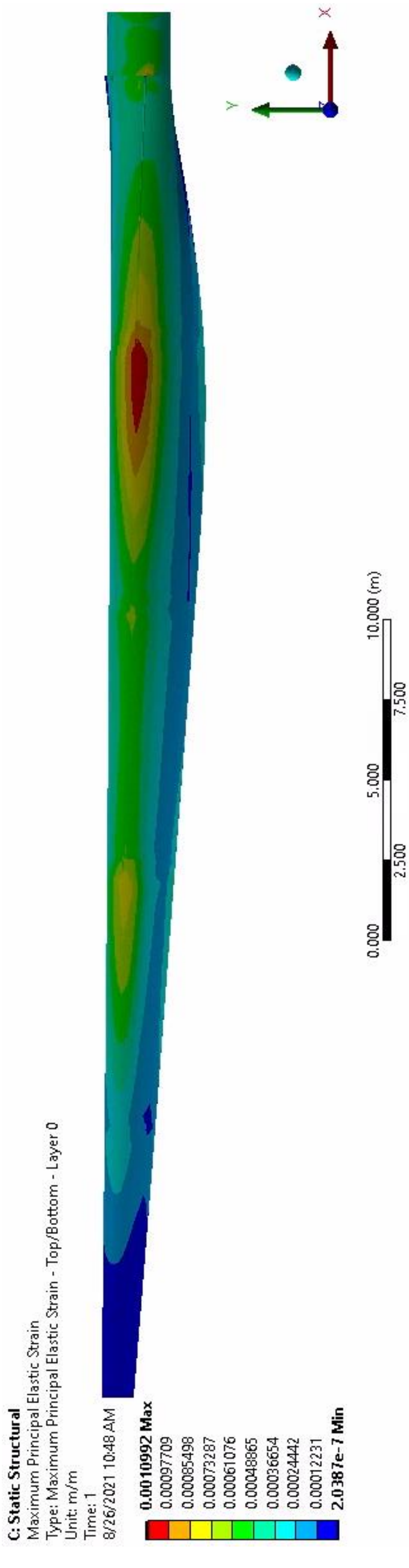


Figure 25 - Maximum principal strain for the glass/epoxy turbine blade

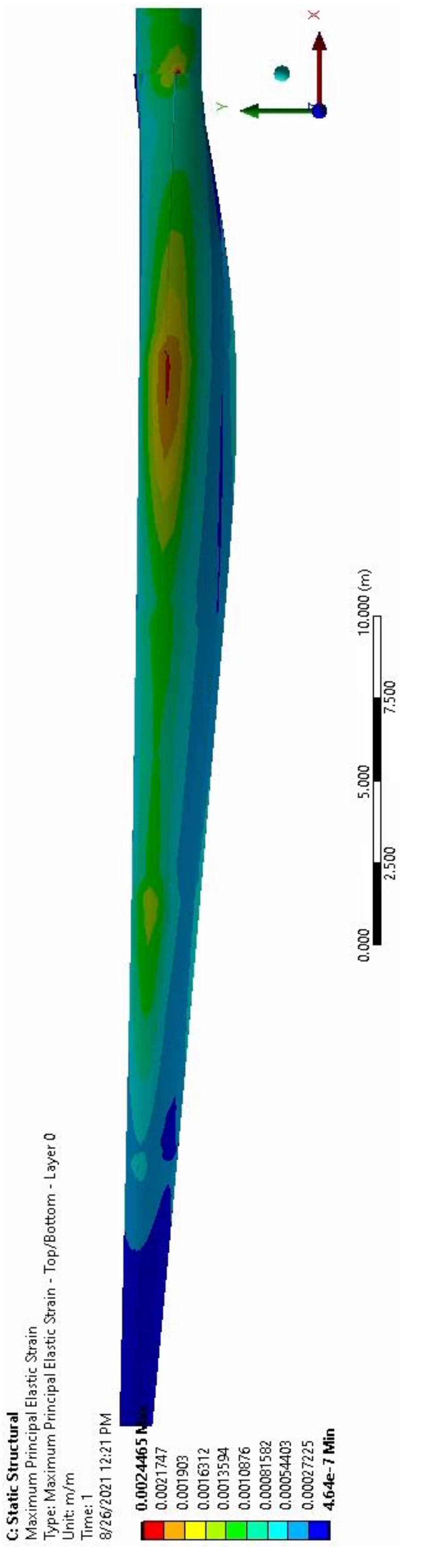


Figure 26 - Maximum principal strain for the flax/PP turbine blade

6.3 Case Study

As the shown in the previous section the turbine blades that used more sustainable materials performed worse when compared to the glass fibre and epoxy matrix blade. However, these blades were lighter than the glass epoxy blade which suggests an opportunity to improve the performance of the blades by adding more materials. Due to time constraints on the project, it was not possible to do this for all the turbine blades, so the hemp fibre and PLA matrix was chosen as a case study. These materials were chosen because it was the best performing turbine blade material that used sustainable fibres and matrix.

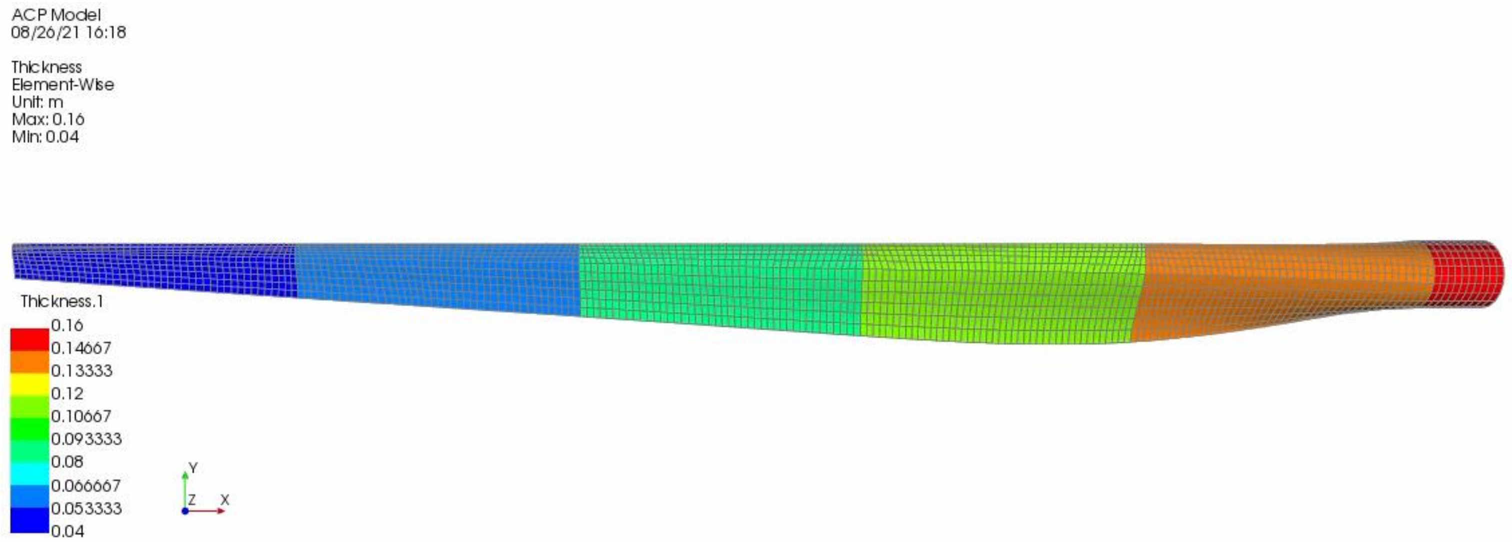


Figure 27 - Thickness of the case study hemp fibre and PLA matrix blade

To improve the performance of the turbine blade and increase the mass of the blade to match that of the glass fibre and epoxy blade a rudimentary scale up of the stackup layer of the composite materials was performed. The hemp fibre and PLA matrix turbine blade (22197 kg) is approximately a third lighter than the glass fibre and epoxy matrix turbine blade (34082 kg). Therefore, the amount of stackup layers used for all the areas of the turbine blade were scaled up by approximately a third. The final thicknesses are shown in Figure 27. The thickest section has increased from 0.104 m to 0.16 m and the thinnest section has increased from 0.024 m to 0.04 m

After the layer of the stackup had been redefined the model was simulated in the same way that was described in section 5.0.

The results for the new and the orginal hemp fibre and PLA matrix turbine blade are shown in Table 6. The maximum deformation has decreased by 0.6634 m which is a significant improvement. The deformation is shown in Figure 29 and Figure 30. The deformation is still showing the same characteristics as the previous turbine blades; this gives confidence that the model is working in the same way as in the other models. The maximum and average equivalent von Mises stress has also decreased showing that the new turbine blade is more robust. Simarily, the maximum principal stress and strain results have decreased, further showing that the turbine blade mechanical performance has improved.

Table 6 - Modelling results for the original and new hemp fibre and PLA matrix turbine blade

Material		Mass (kg)	Max deformation (m)	Equivalent v Mises Stress (MPa)		Max Principal Elastic Strain (m/m)	Max Principal Stress (MPa)
Fibre	Resin			Max	Average		
Hemp	**PLA**	22197	2.2585	43.695	3.5591	0.0023809	41.266
Hemp	**PLA**	31868	1.5951	36.741	2.8397	0.0020234	34.881

Figure 28 compares the maximum deformation of the new hemp fibre and PLA matrix turbine blade against the other turbine blades. The new hemp fibre and PLA matrix turbine blade has improved significantly compared to the orginal. It is now performing close to the glass fibre turbine blades which suggests that it may be possible to replace the glass fibre and epoxy materials based on this metric. As the weight has increased to a comparable level to the glass fibre turbine blades the advantage of the lighter material has now been negated. However, as hemp and PLA are natural materials, despite this there should be less negative impact on the environment.

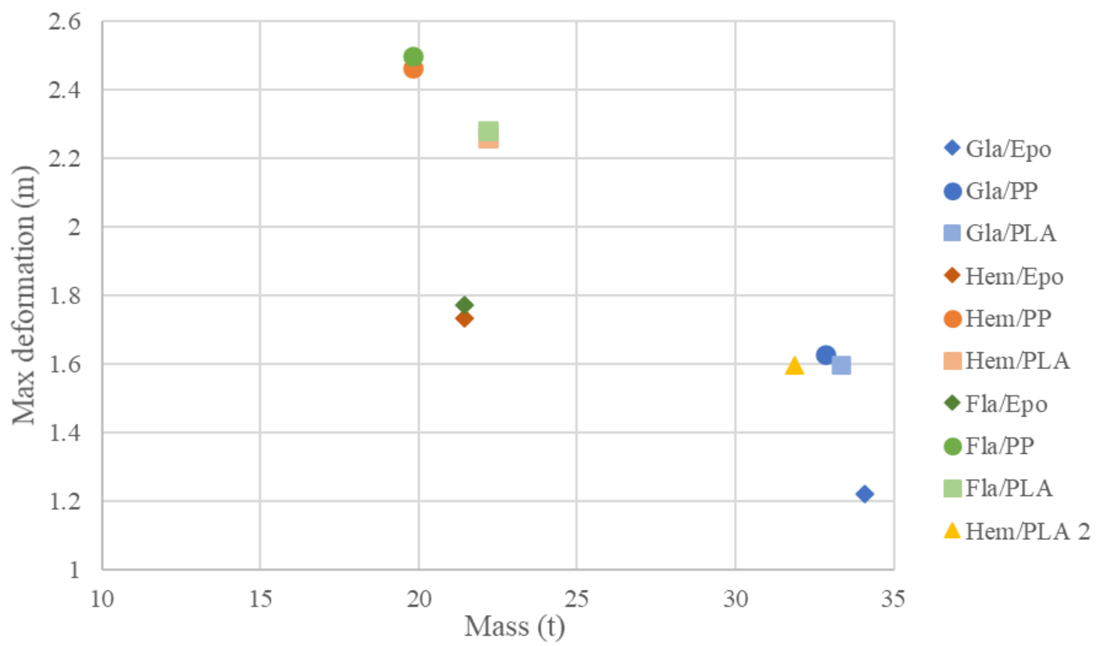
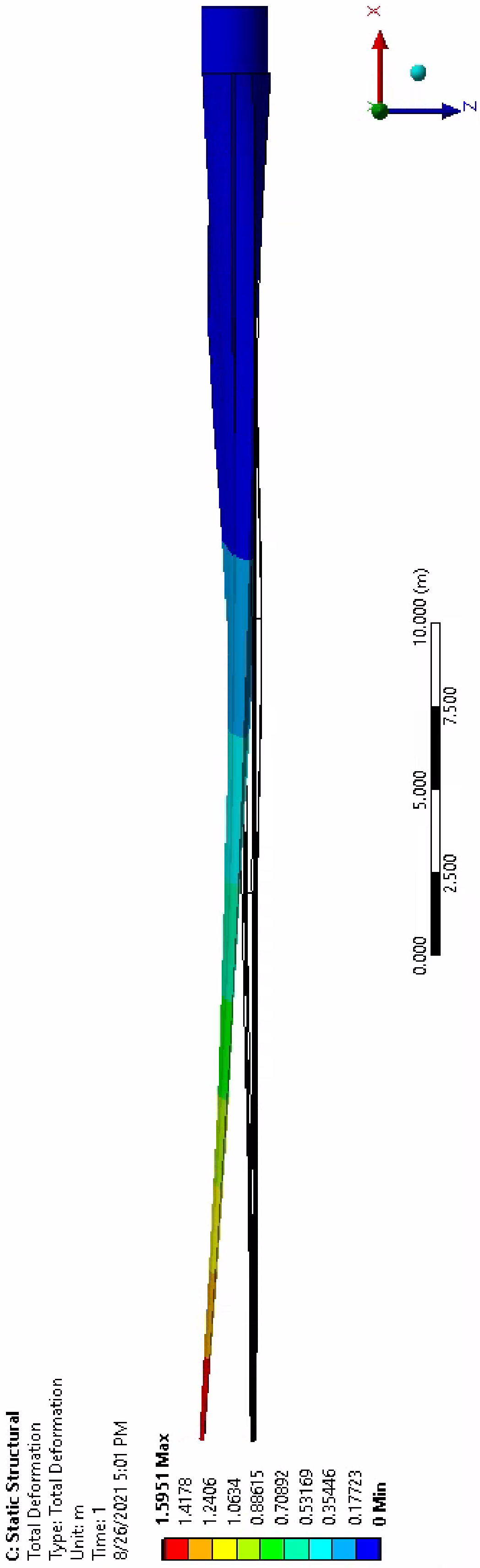


Figure 28 - Plot of max deformation against mass for all the turbine blades modelled



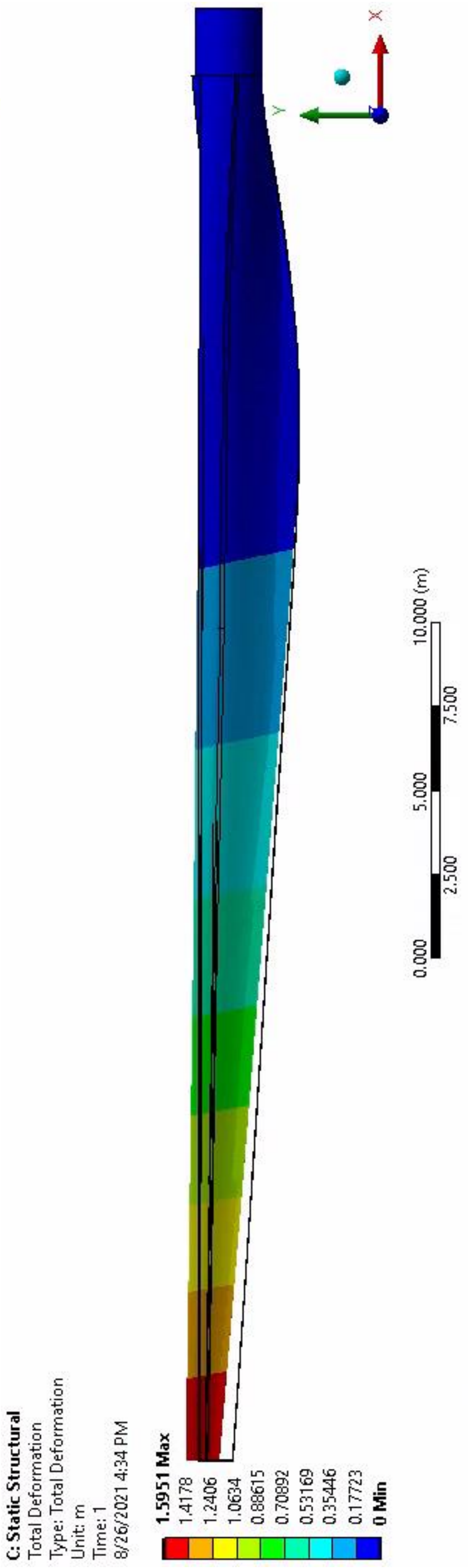


Figure 29 – Side view of the deformation of the new hemp fibre and PLA matrix turbine blade

Figure 30 - Top view of the deformation of the new hemp fibre and PLA matrix turbine

7.0 Discussions and Conclusion

The aim of this project was to determine whether it is possible to reduce the negative environmental impact from the manufacturing, construction and operation of wind turbines. From the evidence considered in the literature review, the project was narrowed down to focus on whether the environmental impact of HAWT blades, which are predominately made of glass fibre composites, can be reduced. The project investigated the potential for natural fibres (hemp and flax) and more sustainable matrix materials (PP and PLA) to replace glass fibre composites. To do this, wind turbine blades composed of sustainable composites were modelled in ANSYS. They were then compared to the glass fibre and epoxy resin turbine blade using metrics such as the deformation, von Mises equivalent stress and the mass of the blades.

The modelling showed that the natural fibre turbine blades had significantly more deformation than the reference blade. However, the mass of the turbine blades using natural fibres was approximately two-thirds of the glass fibre composites. Therefore, a case study using the best performing sustainable composite (hemp fibre and PLA matrix) was undertaken to investigate the effects of increasing the amount of composite used to a more comparable mass. As a result, the maximum deformation was significantly less, reducing from 2.26 m to 1.60 m at the tip of the 43.2 m blade. This is a promising result for a composite made of completely biodegradable materials, and compares to the glass fibre and epoxy matrix wind turbine blade which had the maximum deformation of 1.22 m. However, in interpreting this result it needs to be recognised that the deformation of all blades appears to be large which could be due to the significant length of the blade, although it could also be due to inaccurate modelling or the simple blade design; this is considered further below.

As the sustainable composite materials show promising, but at this stage inferior, properties to the glass fibre composite, the use of hybrid composites, which use a mix of synthetic and natural fibres may be a practical solution. Investigating hybrid composites, however, was outside the scope of the project, and there is already significant research being done it this area [99].

7.1 Considerations

The scope of the investigation was limited by the time and resources available, made more difficult due to ongoing effects of the COVID pandemic.

A limitation of the literature review was that it failed to identify direct comparisons for the sustainable composites and the turbine blade modelling. This meant that the results from the modelling could not be validated more robustly. This limitation could be due to the lack of research that has been done in this area, as well as relevant research being missed due to the search strategy used for finding evidence.

Another consideration from the literature review was that there was a range of values identified for each material mechanical property, and so average values were selected for use in the modelling. Therefore, the results were not the best possible outcomes that could be achieved using these sustainable composite materials. It is possible that more effective processing techniques could be used which might yield materials with consistently superior mechanical properties which in turn would lead to more promising results. With progress in the research and development of these alternative materials, the robustness of the results will improve as there will be more established mechanical properties to use in the modelling.

Another way to produce more valid material properties of the composites could have been to physically test them in a laboratory. However, this was not possible due to limitations caused by COVID-19 and time constraints.

There were many assumptions made during the modelling that need to be considered and addressed in future studies. One assumption was that there would be perfect bonding of composites and no manufacturing defects. In practice, this is unlikely to be achieved. Consequently, this meant that there may have been an overestimate of their mechanical properties. Although this would also be the case for the glass fibre and epoxy composite, the manufacturing of these composites is a more mature process and hence they are more likely to be consistent and of high quality.

A further assumption in the modelling was that the natural fibres were untreated. Research has shown that to combat the effects of moisture absorption and improve the mechanical properties of natural fibres, coatings are needed [57]. Modelling the effect of such coatings was outside the scope of this project, but it is likely that they would have significant effect on the performance of natural fibres. To understand the sustainability of the coating more research would need to be conducted.

In addition, the results are based on the reported properties of the material as described at the time of their manufacture. However, in reality there will be degradation to the fibres and the matrix. This is pertinent for the natural fibres as they likely to degrade faster, particularly if they absorb moisture which was discussed in section 2.2.2 (page 9). The composites using PLA in the matrix could also degrade faster than expected as PLA biodegrades when exposed to certain environmental conditions such as moisture and heat.

To avoid accelerated degradation, coatings could be applied to the natural fibres and the outside of the turbine blade. This could act as a barrier to moisture which would help preserve them. As mentioned in section 2.2.2 (page 9), coating the natural fibres could also improve the mechanical properties. The use of coatings, and how this effects the degradation and mechanical properties of the composite materials, would need to be investigated further to model their effects more accurately for wind turbine blades.

Finally, the investigation was limited by the assumption over wind speed which meant that the aerodynamic load was only calculated at 12 m/s, a typical rated wind speed for similarly sized wind turbine blades. Before being able to judge whether a new material can be used for a wind turbine blade, modelling at more extreme, storm conditions is required. This is needed to investigate whether the material is expected to become significantly damaged and whether it could survive the required lifecycle of a wind turbine blade. In these conditions the maximum deformation would be significantly larger, which could be an issue for the natural fibre wind turbine blades as the stress and strain may increase significantly. This needs to be further investigated before testing these experimental materials on a wind turbine.

7.2 Conclusion

In conclusion, this investigation has shown a need to improve the sustainability of wind turbine blades, which according to current trends is likely to become an increasingly significant environmental issue. The evidence from the literature together with the modelling undertaken here has identified that natural fibres, such as hemp or flax, together with sustainable matrix materials have the potential properties to allow the environmental impact of wind turbine blades to be reduced. However, significant performance issues were identified which need to be addressed before development of a prototype can be recommended. There is a need for further research; this is discussed in Section 8.0.

8.0 Future Work

To expand on the findings from this project there are numerous future investigations that need to be undertaken. The first would be to validate the results found in this project. This could be done by conducting the laboratory tests on physical composites described in section 5.8 (page 34). This would allow comparison between the material properties used in the modelling and the realistic properties that can be achieve for the composites. The investigation could also be expanded to include a broader range of natural fibre and sustainable matrix materials to ensure that the best performing materials are used. Additionally, the use of coatings would be explored to understand the benefits they can have on mechanical properties of natural fibre and reduced moisture absorption, which would also be tested on physical specimens in a laboratory.

Using the case study as a starting point, an investigation into whether increasing the mass of sustainable composite used could reproduce the performance of the glass fibre and epoxy matrix composites. The use of hybrid composites (for example, hemp and glass fibre together) could also be included in this investigation and would give an idea of the mass of each type of material needed to reproduce the performance of current turbine blades.

With the required mass of material needed to achieve optimal performance, a full LCA could be conducted on each type of blade. This would give a definitive answer on how the sustainability of different types of blades compare. This would then be a useful metric to evaluate the trade-offs between performance and sustainability. This would also involve investigating the end-of-life options for all the materials used and putting further research into understanding the technology available to reduce their negative impact.

Once the best performing composites have been selected, physical models could be manufactured so that physical testing could be performed. This would start with smaller blades that would be modelled to show any discrepancies between the physical and theoretical performance. There could also be work done to improve the design of the turbine blade and how the composites are being used. More complex models and designs could be made to bring the design up to date with the latest turbine blades which have more complex spars as well as using other materials to help improve their performance.

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9.0 Appendices

This section shows some figures and data that may be useful for reference and further understanding of the results obtained in this project.

9.1Additional Case Study Results

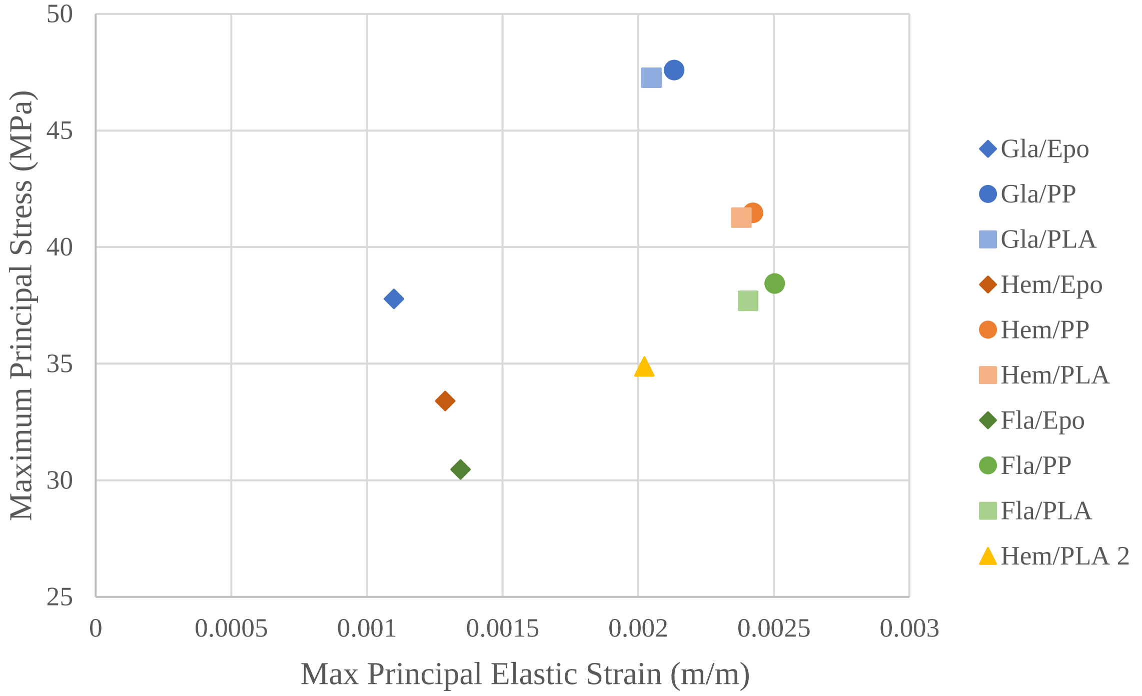

Figure 31 - Plot of the stress and strain with the added case study turbine blade

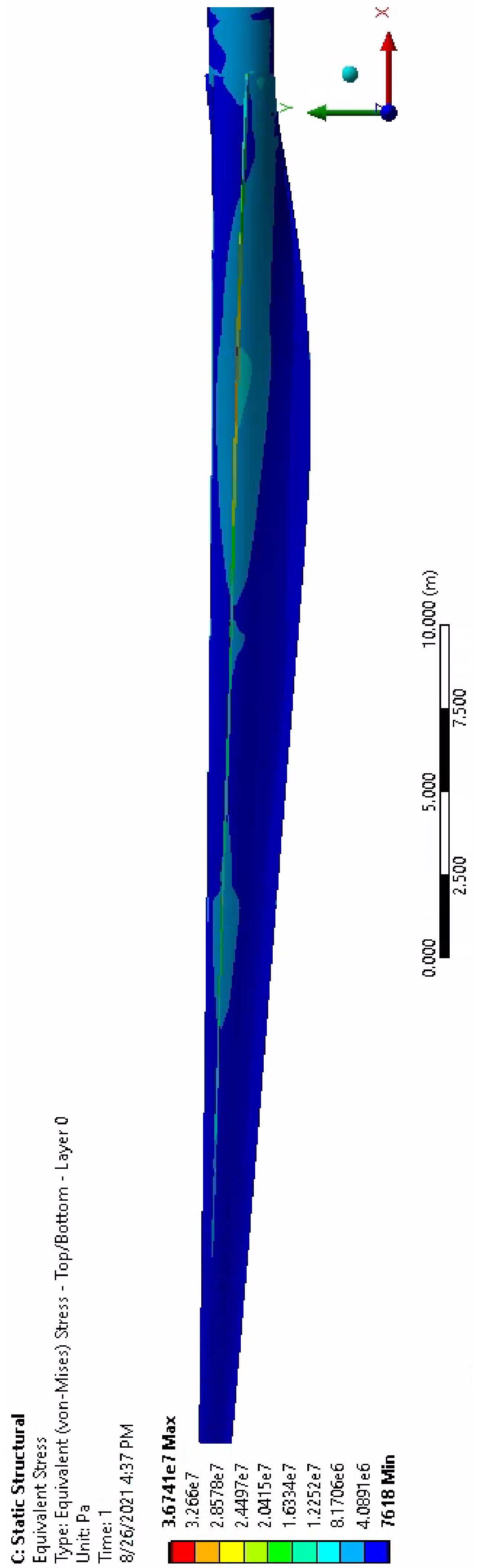

Figure 32 – Representation of the principal stress for the case study turbine blade

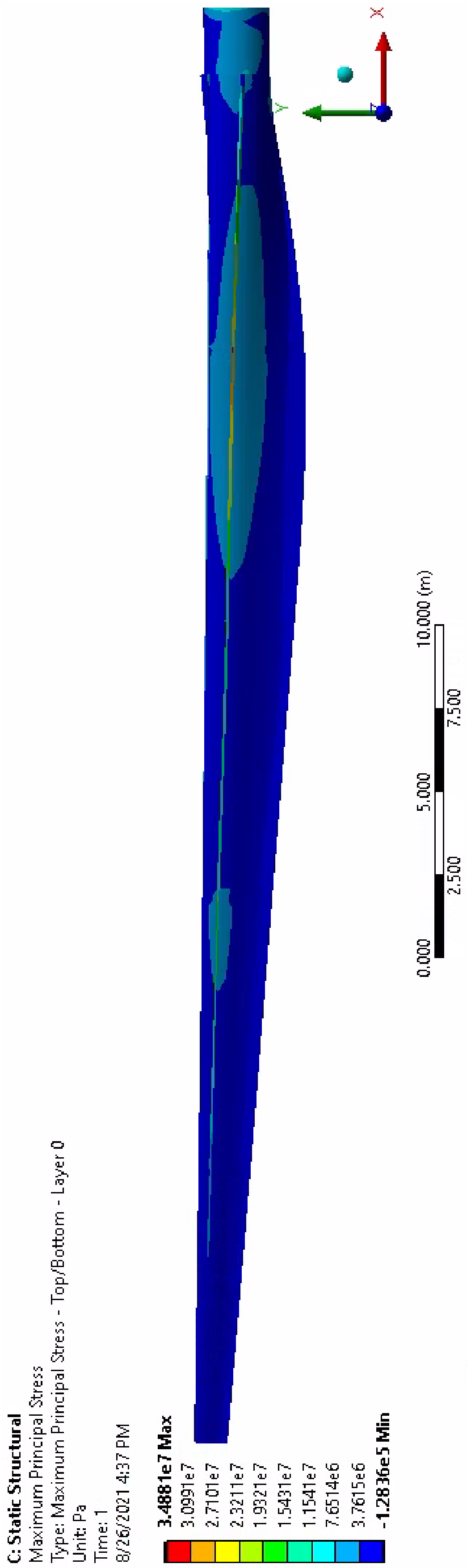

Figure 33 - Representation of the principal strain for the case study turbine blade

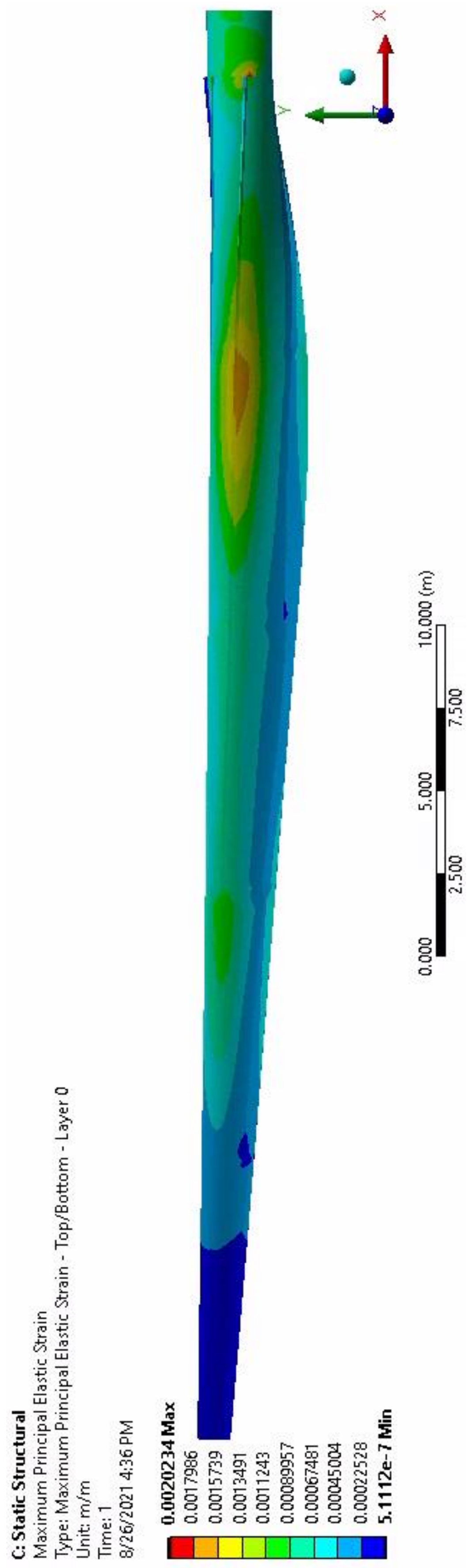

Figure 34 - Representation of the von Mises equivalent stress for the case study turbine blade