The Application of Bio-based Composites in Wind Turbine Blades

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Abstract:

Wind energy is a sustainable alternative to traditional fossil fuel sources. Improvements are constantly being made to maximize turbine efficiency, which is only increasing wind's potential to be viable on a large-scale. Blades must be constructed using low density materials with high stiffness. To meet this criteria manufacturers gravitate towards composite materials to achieve the necessary mechanical properties. Composites are simply two or more materials combined and they are advantageous in their ability to provide superior mechanical properties than each material would individually. In a wind turbine blade, the class of composites used are fiber reinforced composites (FRC) which consist of long fibers embedded in a resin matrix. The materials of choice for FRC turbine blades are often synthetic glass fibers set in epoxy resins due to their ability to perform well at relatively low cost. However, synthetic materials are not readily biodegradable and the thermoset nature of the composite blades make recycling challenging. The use of bio-based composites opposed to the current synthetic materials in wind turbine blades could mitigate the issues that come with end of life disposal while still providing composite strength. Fully biodegradable blades could allow for improvement in the sustainability of wind turbines. The mechanical properties, design and feasibility of bio-based composite wind turbine blades are explored. The findings suggest that many fibers such as jute, hemp and flax could perform similar to synthetic glass fibers with several modifications and bio-based resins also demonstrate good properties in comparison to traditional epoxies.

Introduction:

Three main components of wind turbines are the tower (the tall base), the nacelle (the box which contains the generator components) and the blades. The two main sources of load that the blades experience are wind and gravity. It's critical that blade design allows for the materials to withstand those loads for sustained periods of time and harness wind efficiently so it can create energy even from minimal wind. Consequently, the blades are the most costly component of the turbine [1]. When choosing materials for wind turbine blades, there are many important things to consider, specifically density and stiffness. High stiffness is important because it prevents the blade from bending and colliding with the tower. Low density is also essential because it allows for thinner and lighter blades. Early windmills were made using primarily metal blades, although they could not withstand many stress cycles before failure and experienced metal fatigue. As metals showed their inherent limitations as a materials for blades [1], manufacturers moved towards the use of composites.

Glass fibers are the most common fiber in the industry as they are cheaper than carbon fibers, have moderate stiffness, high strength and moderate density. Carbon fibers on the other hand have high stiffness, high strength, and are very low density, however they are very expensive at approximately $10.0 per lb [2]. The fibers in a composite act as reinforcements to an epoxy resin. Epoxy resins are polymers, which are large molecules made up of chains of smaller molecules. Large molecules have large intermolecular forces holding the bonds together which in turn creates strong, thermoset (concrete) materials.

The epoxy resin/fiber composites can be constructed using a variety of techniques, although the vacuum assisted resin transfer molding process (VARTM) is most prevalent in the wind turbine blades manufacturing. In this technique the epoxy resin is then injected into fibers in a mold of a blade under vacuum pressure [1]. This technique is effective because it only introduces the optimal amount of resin and the excess is pulled out by the vacuum hence maximizing the fiber volume fraction. Typically, high fiber content is a crucial factor in achieving high performance composites [3]. Once the fibers are injected and cooled, the thermoset resin will never return to liquid form.

At the end of composite life cycles, the components are closely interconnected, relatively stable and difficult to recycle [4]. The unrecyclable nature puts wind turbine blades in the landfill. The end of life waste from wind turbine blades is predicted to exceed 500 kilo tonnes annually by 2029 and to continue increasing rapidly thereafter [5]. For context, commercial blades are required to generate 500kw-5Mw of power and for every one-kilowatt of wind power, there are ten kilograms of materials [6]. If blades made from bio-based composite materials can perform mechanically similar or even better than synthetic materials, it could decrease the waste issue and further enhance the sustainability of wind turbines. Multiple types of natural fibers, as well as bio-based resins are going to be explored.

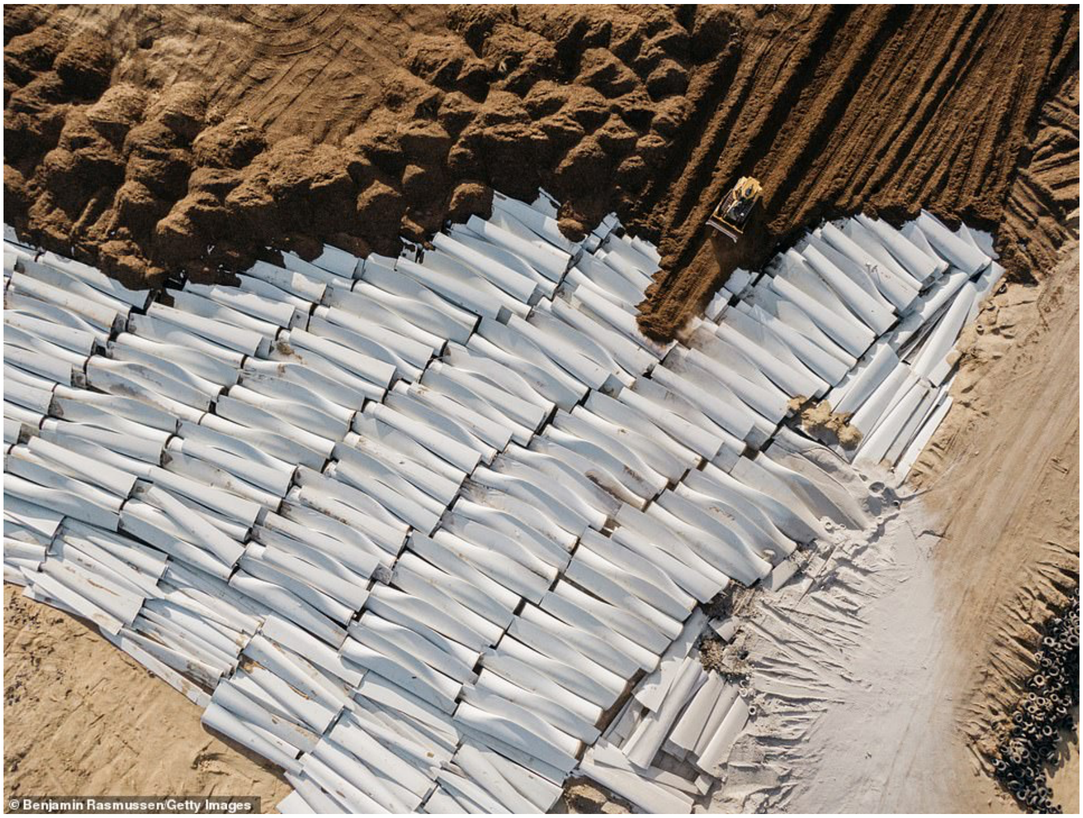
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Figure 1 Wind Turbine Blades in a landfill [24]

Discussion:

Properties of Some Common Synthetic and Natural Fibers:

Density and elastic modulus values for natural fibers were collected from a study [7] which compared 17 different studies of mechanical properties listed for these natural fibers. Due to high variability the data is given as a range and specific strength was calculated by dividing the lowest and highest elastic modulus found in literature by the average density found in literature. The data for synthetic fibers was found in a study [8].

Fiber	**Density (g/cm^3)**	**Elastic modulus (GPa)**	**Specific strength (GPa*cm^3)/g**
Carbon Fiber	1.4	230-240	164-171
E-Glass	2.5	70	28
Jute	1.3-1.5	3-55	2-39
Flax	1.2-1.5	23-103	17-76
Hemp	1.4-1.5	3-90	2.1 -63

In composite materials, fibers create strength and stiffness (carry the loads and stress), hence why they are so important. As presented in the chart above, the data in literature about the properties of natural fibers has a considerable amount of variability because fibers occur in nature and mechanical properties are affected by external factors. The variability is an obstacle that can sometimes hold back the application of natural fibers in high performance areas such as wind energy. Nonetheless, the mechanical properties and overall behavior of many natural fibers have been widely studied as possible replacements for glass and other synthetic fibers as ‘green’ and more sustainable products are gaining traction to combat environmental issues.

Synthetic fibers are environmentally taxing due to the large amounts of energy consumed in production. In contrast, natural fibers consume very little energy in production, are abundant, potentially lower cost, lightweight and safer to handle than synthetic fibers. Natural fibers can be broken into categories such as bast, leaf and seed to name a few. Bast fibers provide structural support for plants, so they have the most potential for high performance applications. Bast fibers can exhibit strength up to 7000MPa and stiffness up to 70GPa [9]. Common bast fibers studied include jute, hemp, flax, kenaf, ramie and sisal.

In a study conducted by Shah et al., two identical blades were molded using an unsaturated polyester resin reinforced with either E-glass or flax fibers. Although the glass composite had overall better mechanical properties, it was observed the specific tensile stiffness and effective tensile stiffness were comparable between the flax/epoxy composite and glass/epoxy composite. Composite specific stiffness of the flax and glass composites were 17.9 and 20.6 GPa/g cm−3 respectively. The effective fibre stiffness was 67.7 GPa for the flax and slightly higher for the glass at 81.6 GPa. The flax blade was also 10% lighter and had 60% density of the glass blade [10]. The study reveals the lightweight and stiff nature of flax therefore showing possibility for its use in a turbine blade. Stiffness to weight ratio is essential in a blade as they must have small gravitational loads while still being able to minimize tip deflection so they do not interfere with the tower [1]. The flax blade was also able to withstand the normal operational load and the worst case load with no functional/catastrophic failure [10].

In another study, values for elastic modulus of jute, flax and hemp fibers were 26.5, 27.6 and 70 GPa respectively and the elastic modulus obtained for E-glass was 70 GPa [4]. With such a high elastic modulus, these results suggest that hemp fibers could also be a viable option for high performance applications like a turbine blade as well. In a study done by Wambua et al., hemp composites were tested against coir, jute, kenaf, sisal and the hemp composite showed the highest flexural strength at 54 MPa which was comparable to the strength of a tested glass composite (60 MPa). The specific flexural strength (flexural strength divided by density) of hemp composites (36.5) was actually even higher than that for glass mat composites (about 24) [11].

Research conducted by Karmin et al. highlighted further the potential of functional and sustainable natural composites by testing graphene based natural jute fibers. When jute fibers were coated in graphene and then used in composites, the young's modulus increased from 30 GPa (jute composite without graphene coating) to 78 GPa [12]. They also found that the young modulus was 18% higher than S-glass and 40% higher than E-glass composites [12]. The young's modulus is an important factor in an application like a wind turbine blade because it predicts how a material will perform when subjected to a force. These results make graphene coated jute composites an excellent candidate for a bio-based blade. Not only does the graphene coated jute fiber outperform synthetic glass mechanically, but it also is superior environmentally: glass and carbon synthetic fibers contribute to global warming whereas one tonne of dry jute could absorb 2.4 tonnes of carbon [12]. There are several natural fibers with potential, although the graphene coated jute seems the most promising.

In order to achieve a fully biodegradable wind turbine blade, the natural fibers would need to be coupled with a bio-based epoxy resin. Largely, matrices in high performance composites are petroleum based resins and therefore hinder the sustainability of these products [13]. From a renewability standpoint, thermosets (the type of matrix used in wind turbine blades) such as benzoxazines or polybenzoxazine provide an interesting alternative to traditional polymers [14,15]. Natural raw materials of benzoxazine are found in large quantities in wastes generated from agro-based industries, biomass, and other industries [13]. When the deterioration of a flax/epoxy composite was compared to that of a flax/benzoxazine, it was actually found that the benzoxazine performed better and only lost 20% of it's flexural properties whereas the epoxy composite lost 32% [13]. Two of the bio-based resins that are commercially available are Greenpoxy 55 from Sicomin and EcoPoxy from Ecopoxy Systems USA. Experimental results show that when flax was laminated in a composites with the eco-friendly epoxies (Greenpoxy 55 and EcoPoxy), it showed better mechanical performance than a flax/petroleum based epoxy composite [16]. Out of the resins tested in the work, the Greenpoxy 55 had superior flexural strength and modulus compared to the other eco-friendly epoxy and the petroleum based epoxy. The flexural strength was 112.6 MPa and the modulus was around 5000 MPa. These studies provide data showing better compatibility between bio-based epoxy resins and natural fibers than traditional epoxy resins and natural fibers. Bio based resins are capable of replacing less environmentally friendly resins in natural composites.

Using natural jute fiber and bio-based resin Ecopoxy, a possible bio-based windmill composite design is shown below in Figure 2.1. Fully bio-based resins that can perform well are not yet available, so it's important to note that products such as Ecopoxy and Greenpoxy 55 contain less than 100% bio materials and aren't fully biodegradable, although they are considered bio-based resins that are "greener" than traditional epoxies. The elastic modulus of the jute fibers was found in a study to be 20.1-26.8 GPa [17] and the elastic modulus of the Ecopoxy was found in another study to be 2.54 GPa [18]. From those values, the equations below were used to determine the shear modulus and elastic modulus of a jute/Ecopoxy composite (Figure 3.1). A fiber volume fraction of 0.6 and a matrix volume fraction of 0.4 were used. Poisson's ratios of 0.30 and 0.35 were assumed for the design, as these are common values for composites. A 3D model was created on solid works with the help of my supervisor Eric Lepp. The curved nature of the blade design can be explained by based on aerodynamic principles. The curved side creates an area of low pressure and the flat side creates a high pressure area which then pushes on the blade and generates lift. Narrowing the blade tip end helps minimize drag forces (due to less area) and maximize efficiency.

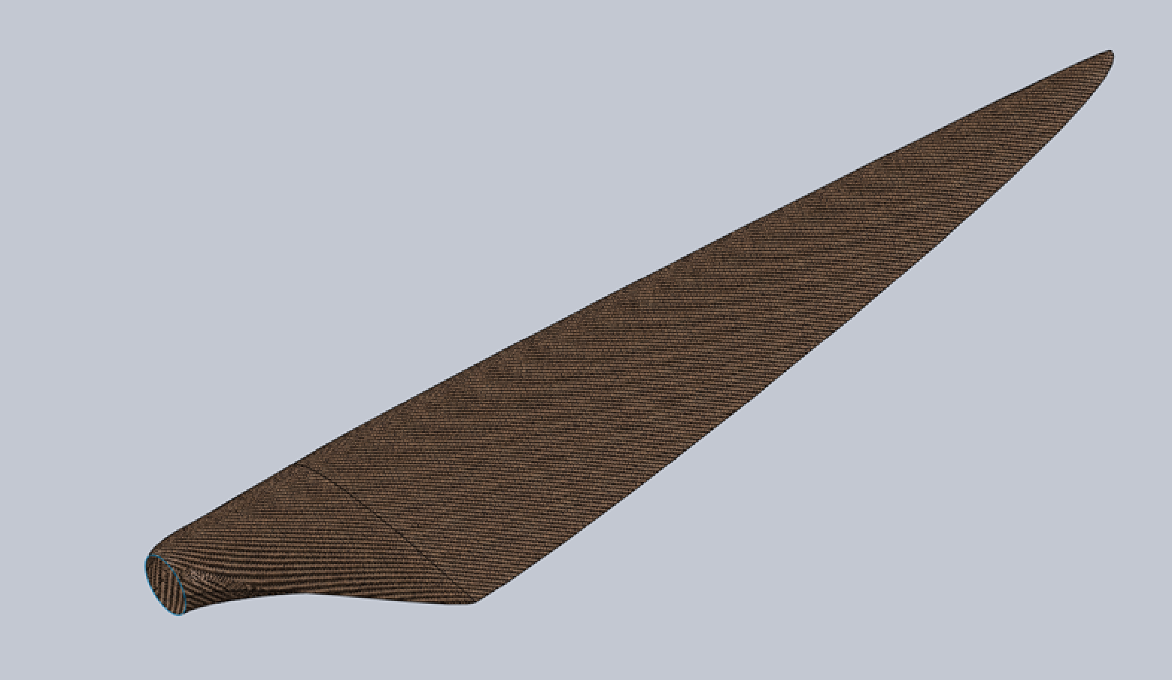

Figure 2 Jute Wind Turbine Blade Model Made on SolidWorks

Composite Material Formulas:

E_c =Elastic Modulus of Composite

$$E_c = E_f V_f + E_m V_m$$

G_c =Shear Modulus of Composite

$$\frac{1}{G_c} = \frac{V_f}{G_f} + \frac{V_m}{G_m}$$

E_f =Elastic Modulus of Fibers	E_m =Elastic Modulus of Matrix
G_f =Shear Modulus of Fibers	G_m =Shear Modulus of Matrix
V_f =Fiber Volume Fraction (usually approx. 0.6)	V_m =Matrix Volume Fraction (usually approx. 0.4)

Further calculations were done using a python code that allowed more properties of the jute/Ecopoxy composite (traverse and longitudinal elastic modulus of composite). The python code is shown in the appendix.

Using the values of shear and elastic modulus of fibers and matrix, the poisson's ratio and the fiber volume fractions and matrix volume fraction in a python code, the transverse and longitudinal elastic modulus of the theoretical jute/Ecopoxy were found for angles ranging from 0-90 and then plotted on the graphs below using Excel (Figure 3 and 4). The angles at which the fibers are orientated influences the strength of a composite in both directions. To optimize strength and stiffness fibers should be aligned parallel to direction of loading [17]. In figures 3 and 4, the graphs of the longitudinal (lengthwise) and traverse (widthwise) elastic modulus respectively are shown as functions of fiber angles ranging from 0 to 90 degrees. As figure 3 shows, when the fibers are oriented at 0 degrees, they are at the maximum longitudinal elastic modulus, then as fiber angle increases, the elastic modulus decreases until it is at its lowest longitudinal elastic modulus at 90 degrees. Conversely, shown in figure 4, 0 degree fiber orientation results in the minimum transverse elastic modulus and from there the graph shows growth until the fibers have reached 90 degrees where they are at the maximum elastic modulus in the transverse direction. In a braided composite design, a fiber angle 30-60 degrees would be the optimal range to orient the natural fibers.

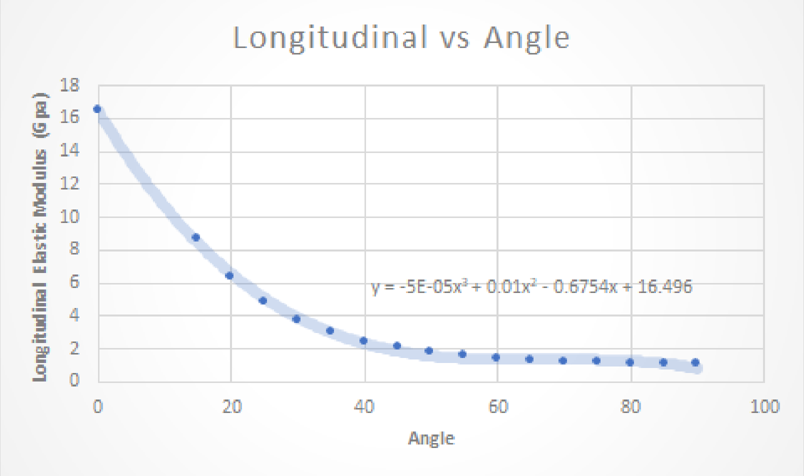

Figure 3 Longitudinal Elastic Modulus as a function of Angle

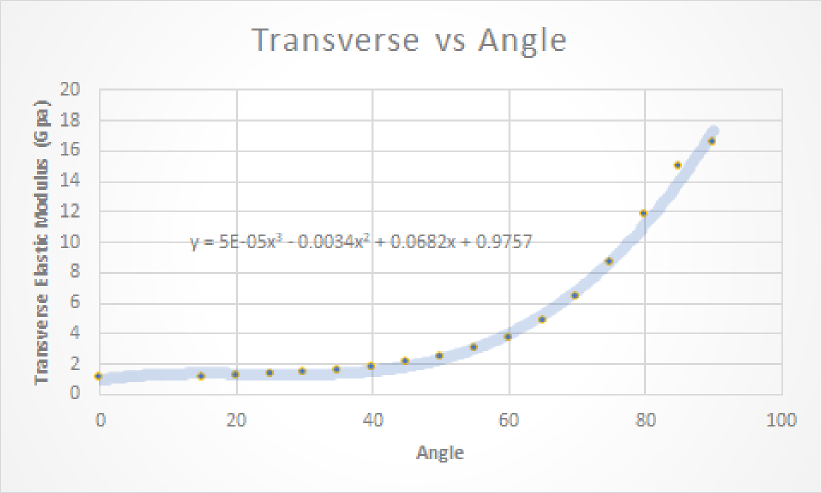

Figure 4 Transverse Elastic Modulus as a function of Angle

It is important to note that the theoretical composite proposed does not take into account certain factors that could hold back the use of bio-based composites such as fiber content, hydrophilic nature of natural fibers, variability in natural fibers and processing techniques [19]. For high performance applications it can be difficult to implement natural fibers as a result of the high variability caused by the source of fibers, method of extraction, maturity, growing conditions, harvesting period, and modification [20]. In order for composites to truly experience the benefits of combining the mechanical advantages of multiple materials, they must be able to properly transfer stress from the matrix to the fibers. The key to ensuring the stress is transferred properly in a composite is by maximizing the interface adhesion between the fibers and resin. Interface adhesion is the area where two materials meet and it must be strong in order to have a successful composite. A common drawback with natural fibers is interface adhesion with matrices. Plant fibers have high moisture absorption which is an issue when composite with hydrophobic matrix polymers [8]. In addition to the hydrophilic nature of these fibers which absorb water easily, natural fiber surfaces have waxes and other non-cellulosic substances such as hemi-cellulose, lignin and pectin, which create poor adhesion between matrix and fibers [3]. One way to combat this problem is through chemical treatment of the fibers, using alkaline solutions and various other surface modifications. One of the most popular surface alkaline treatments is sodium hydroxide [3]. Surface treatments are commonly shown in studies to improve the fiber matrix binding and consequently help natural fiber reinforced composites exhibit better mechanical properties [8,12, 21-23]. In one study, jute fibers were treated with alkali and a 120% increase in tensile strength and modulus by 150% was observed [22]. Moreover, nanomaterials have been explored to improve the interface adhesion between natural fibers and the resins. Nanoparticles (inorganic materials with a surface area of less than 100 nm) can act as a compatibilizer, meaning they react with the natural fiber by removing lignin and cellulose from fiber surface to bring better fiber matrix interaction and therefore better mechanical properties [20].

Conclusion:

There are many possibilities to incorporate bio-based composite materials into a high performance application such as a wind turbine blade. Hemp, flax and jute are good options. The highest capability in terms of mechanical performance are graphene coated jute fibers. There are also replacement options for regular epoxy such as bio-based resins like Greenpoxy and Ecopoxy. Although challenges do arise such as variability when working with natural materials, there are several modification processes available to lessen the issue. By utilizing materials provided by nature to create stiff and low density composite materials, it is possible to have highly efficient blades that can provide completely clean wind energy.

Acknowledgments:

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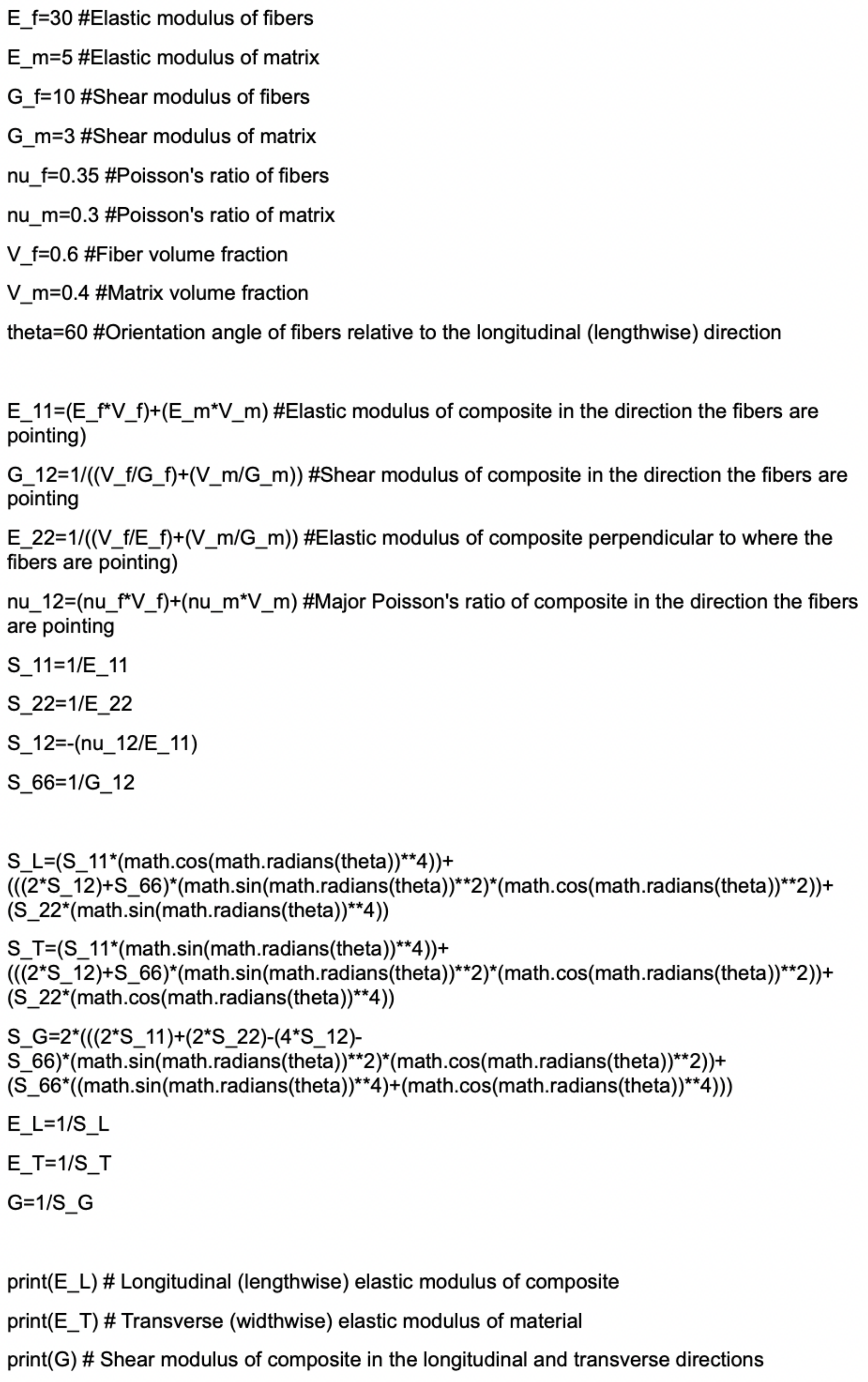
Appendix:

Python code used for transverse and longitudinal elastic modulus values based on angle.



```
E_f=30 #Elastic modulus of fibers
E_m=5 #Elastic modulus of matrix
G_f=10 #Shear modulus of fibers
G_m=3 #Shear modulus of matrix
nu_f=0.35 #Poisson's ratio of fibers
nu_m=0.3 #Poisson's ratio of matrix
V_f=0.6 #Fiber volume fraction
V_m=0.4 #Matrix volume fraction
theta=60 #Orientation angle of fibers relative to the longitudinal (lengthwise) direction

E_11=(E_f*V_f)+(E_m*V_m) #Elastic modulus of composite in the direction the fibers are
pointing)
G_12=1/((V_f/G_f)+(V_m/G_m)) #Shear modulus of composite in the direction the fibers are
pointing
E_22=1/((V_f/E_f)+(V_m/G_m)) #Elastic modulus of composite perpendicular to where the
fibers are pointing)
nu_12=(nu_f*V_f)+(nu_m*V_m) #Major Poisson's ratio of composite in the direction the fibers
are pointing
S_11=1/E_11
S_22=1/E_22
S_12=-(nu_12/E_11)
S_66=1/G_12

S_L=(S_11*(math.cos(math.radians(theta))**4))+
(((2*S_12)+S_66)*(math.sin(math.radians(theta))**2)*(math.cos(math.radians(theta))**2))+
(S_22*(math.sin(math.radians(theta))**4))
S_T=(S_11*(math.sin(math.radians(theta))**4))+
(((2*S_12)+S_66)*(math.sin(math.radians(theta))**2)*(math.cos(math.radians(theta))**2))+
(S_22*(math.cos(math.radians(theta))**4))
S_G=2*(((2*S_11)+(2*S_22)-(4*S_12)-
S_66)*(math.sin(math.radians(theta))**2)*(math.cos(math.radians(theta))**2))+
(S_66*((math.sin(math.radians(theta))**4)+(math.cos(math.radians(theta))**4)))
E_L=1/S_L
E_T=1/S_T
G=1/S_G

print(E_L) # Longitudinal (lengthwise) elastic modulus of composite
print(E_T) # Transverse (widthwise) elastic modulus of material
print(G) # Shear modulus of composite in the longitudinal and transverse directions
```

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