Interim Design Report

Taller Wind Turbine for Low Wind Speed Regions

Team Number: 25

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I. Group Members Information

The team is composed of four senior mechanical engineering students and two senior civil eningeering students. All students attend Florida State University.

Steven Blanchette is currently in the Mechanical Engineering BS-MS program and will graduate in May 2016. He currently serves as the Treasurer of Pi Tau Sigma, a Mechanical Engineering honor society. After graduation Steven has the opportunity to return to N.L. Racing Technologies, a NASCAR Engineering firm.

David Delie is a current senior in Mechanical Engineering at the FAMU-FSU College of Engineering. Once he graduates he plans to find a job relating to material science. He also has aspirations of obtaining an MBA after a few years in industry.

Kimberly Martinson is a civil engineering student anticipating to graduate Spring 2015. After graduation, she plan to pursue her master's degree as well as a career in structural engineering. Her goal is to contribute to the development of sustainable buildings in order to reduce waste and create a cleaner environment.

Jeremiah McCallister is undergraduate Mechanical Engineering student graduating in Spring of 2015. After he graduates from Florida State he will be attending graduate school to get a PhD. in Materials Science and Engineering and work in a National Lab as a researcher on the next generation of renewable energy.

Abigail McCool is seeking her Bachelor's of Science in Mechanical Engineering. She currently serves as the Vice President of Pi Tau Sigma, a Mechanical Engineering honor society. After graduation, Abigail plans on seeking a job in industry.

Theo Meros is a senior Civil Engineering student graduating in May 2015. Theo has worked at Bridge Engineering firm but has interest in the design of other large-scale architectural structures. After graduation, he plans on working at a structural design firm and achieving a Master's of Science degree online.

II. Acknowledgement

There were several individuals that have helped us throughout this semester. Without help from these people the project would not have made as much progress as it has. We are very thankful for the time they took out of their busy schedules in order to instruct us and make sure we understood how to fix our problem before they let us go. Dr. Sungmoon Jung allowed the group to work on this very exciting project and always made time to attend biweekly meetings and answer any questions we had. Dr. Jung has always been extremely positive even when the team has been confused or stuck on a topic related to the project. Dr. Kunihiko Taira has been an excellent mentor and helped us with approaching the design of the wind turbine blades and always provided great ideas that we had not considered. Dr. Powell at the Center for Ocean and Atmospheric Studies helped us understand how to find the wind speed at different heights and good sites to build the turbine. Dr. Hollis has been very helpful in the modeling of the wind turbine blades in Pro Engineer. Dr. Atul introduced the team to the FAST software that is essential to determining the power output from our designed turbine. The senior design instructors, Dr. Helzer and Dr. Gupta have provided guidance on deliverables and helpful feedback to make sure the team stays on track.

III. Abstract

Current wind turbines are not effective to use in Florida because the average wind speed is too low to provide adequate power. This problem has led to the need for a taller wind turbine that can be used in low wind speed regions. This report outlines the progress the team has made during the Fall 2014 semester on the development of this turbine. So far the group has completed research into wind turbine technology and created initial designs for both the structure and blades of the turbine. Descriptions of the designs and their CAD models are provided in this report. Additionally, decision matrices selecting the optimal designs are provided. The team is currently working on force analysis for each of these designs using FAST software from the National Renewable Energy Laboratory (NREL). The next report will go into further depth of the forces on a wind turbine and how our designs respond to these forces along with material selection for the turbine.

V. Introduction

In order to reduce global carbon emissions and continue to generate electricity, renewable energy is a dependable alternative to current power generation methods. There are many renewable sources to access including wind, solar, and hydro energy. In the United States, wind energy accounts for 30% of all renewable energy generated. To generate power a certain wind speed must be present. Unfortunately, the Southeastern United States does not have sufficient average wind speed to make current turbines viable. The goal of this project is to develop a wind turbine that would be effective in low wind speed regions like the Southeastern United States. By designing a wind turbine that is taller than current turbines we will be able to harness larger wind speeds at higher altitudes. The mechanical engineering students will be working with students from the civil engineering department on developing and designing the tower and blades of a new wind turbine.

This report details a basic background of the project and why there is a need for a taller wind turbine for use in the southeast. To complete the project several objectives and constraints must be met within the class time frame. The team has developed several different design ideas for both the blades and structure of the wind turbine and they are shown in this report. The designs are then compared and the best designs are selected by way of a decision matrix. With progress being made the Gantt chart and allocation of resources have been changed accordingly.

A. Background research

Wind energy is one of the leading sources of renewable energy in many countries. The United States is increasing its investment into renewable clean energy opposed to dirty energy like coal and gas power plants. In 2013, 13% of the country's electricity generated was from renewable sources. Wind power constituted 30% of the total renewable energy generated[1]. The growing use of wind energy in the country has not traveled to the Southeastern United States due to low wind speeds. Most of Florida's renewable energy comes from solar plants. Light winds make commercial wind farms not currently viable[2]. This project seeks to explore new ideas that would make wind power a feasible method to generate power in Florida and the Southeastern United States. Figure 1 below shows average annual wind speeds throughout the United States, higher wind speeds are shown in purple/red.

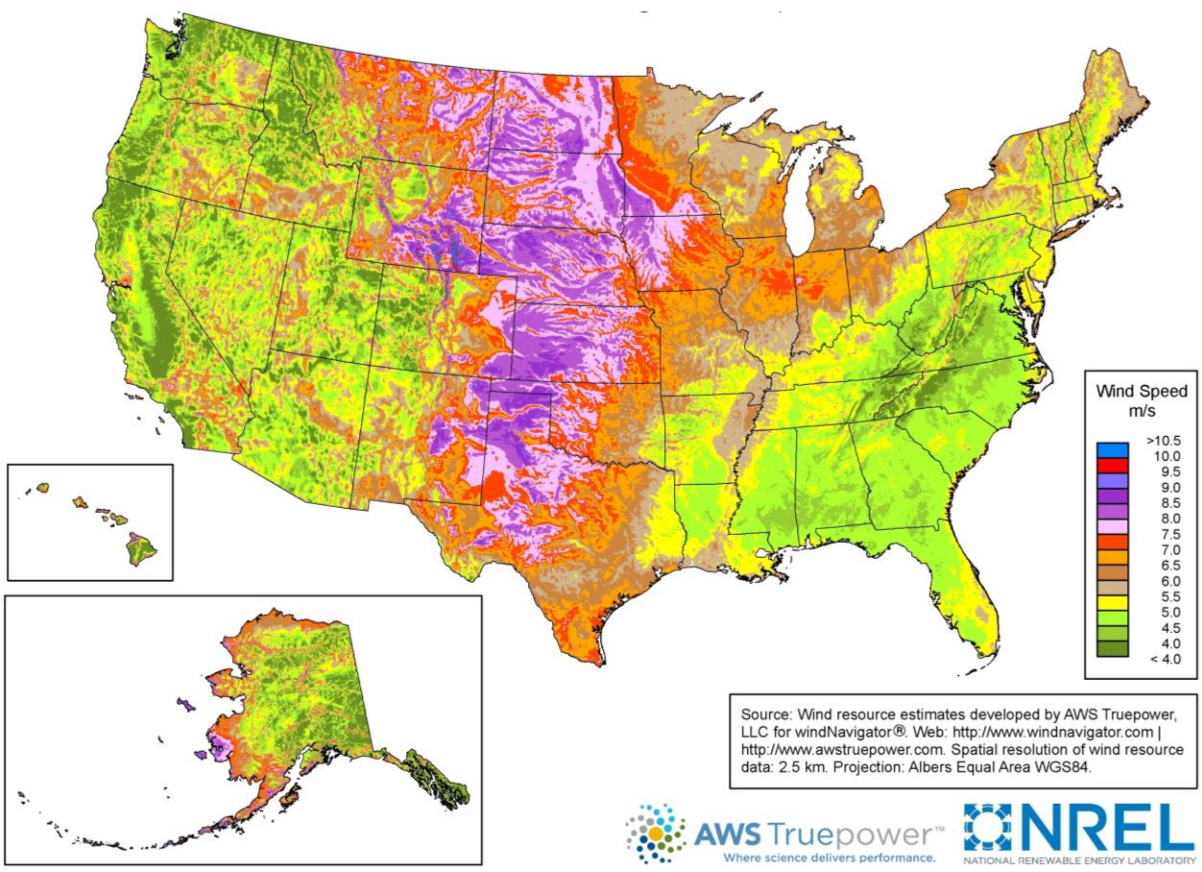


Figure 1. United States: Annual average wind speed at 80m[3]

If there was a wind turbine that could operate effectively at lower wind speeds a huge market, roughly two-thirds of the country, would develop for wind turbine producers. The question then becomes how to make wind turbines work in areas where the wind speed is too low for current turbines to operate effectively. The solution proposed by the sponsor is to make the wind turbine taller so it can utilize faster wind speeds at higher altitudes. The higher wind speed at higher altitudes can be explained by looking at wind flow like water flowing through a pipe with a boundary layer being developed. The velocity vectors will increase with distance from the ground. An example of this wind gradient is shown below in Figure 2.

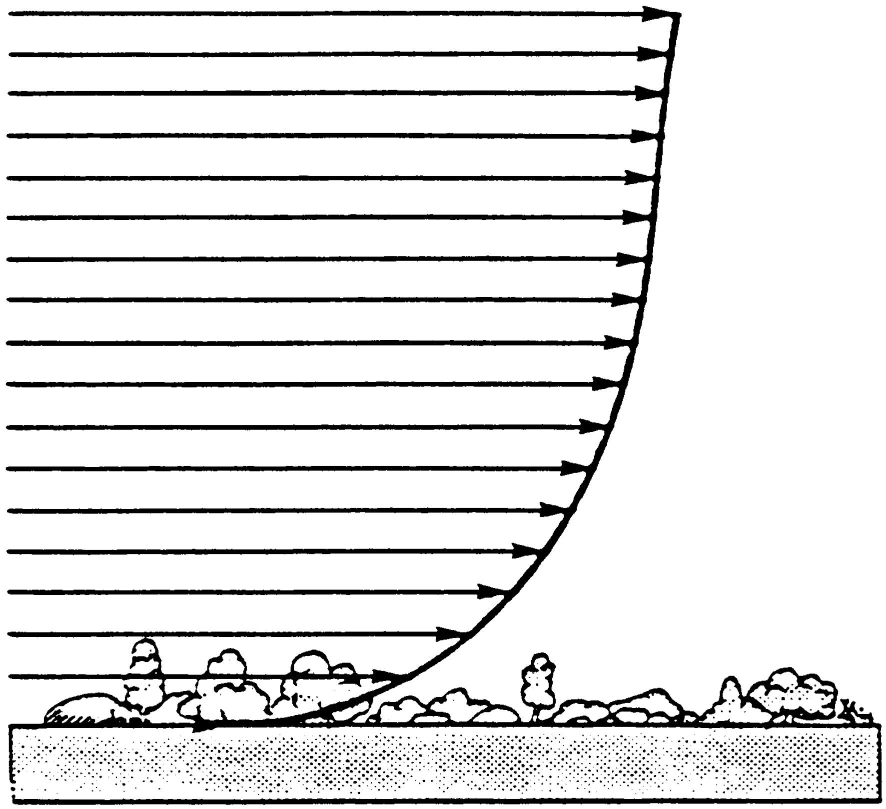


Figure 2. Development of wind gradient with increasing altitude[4]

In order to generate electricity, there must be some sort of input energy. In the case of wind turbines, the input kinetic energy is the wind. This wind causes the blades on a turbine to rotate. These blades are attached to a rotor that spins the generator producing electricity. Currently there are two types of wind turbines used to generate electricity. These include horizontal axis turbines and vertical axis turbines[5]. The issue our senior design team is faced with is the lack of input kinetic energy in low wind speed regions such as Florida. As a result of these low wind speeds, current wind turbines cannot generate sufficient energy. This leaves our senior design group with the task of overcoming the uncontrollable obstacle of low wind speeds and designing a turbine that can generate sufficient energy in low wind speed regions.

The speed of the wind on the wind turbine is critical to generating enough power to be cost-effective. Wind turbines have a “Cut-in Speed” which is the minimum wind speed needed to generate useable power[6]. For most wind turbines this speed is typically 3 to 4.5 m/s. From Figure 1 it can been seen that Florida wind speeds barely make this cut at 80 meters. Since the most common wind turbine used in the United States is 80 meters tall, this project is focused on designing a wind turbine 150 to 200% taller to utilize the higher wind speeds at higher altitudes.

In September 2014, the Energy Department announced that they would be putting $2 million in funding towards two companies in Iowa and Boston focused on producing taller wind turbines in a cost-effective manner[7].

This commitment to taller wind turbines by the government shows that there is a strong incentive to develop this technology for the private and public sector.

B. Need Statement

Our project is sponsored by the FAMU-FSU College of Engineering. The project sponsor is Dr. Sungmoon Jung and he wants the group to focus on using new turbine blade and structural materials that will allow for a new, cost-effective wind turbine to be built in Florida. Currently there are no major wind farms in Florida due to low wind speeds at 80 meters. By introducing a wind turbine that is effective in Florida a new market could exist. There is a need to develop and produce a new type of wind turbine that is larger to utilize wind power in areas like Florida.

"Current 80 meter wind turbines are not cost-effective for use in the Southeastern U.S."

C. Goal Statement & Objectives

Due to the fact that current wind turbines do not exist that can be effectively used in the southeastern united states, this team was presented with the following idea

"Design a new wind turbine that can be used in low wind speed regions to generate electricity"

Objectives:

The goal of the project has several important objectives that the team needs to meet to be successful. They are as follows:

- Incorporate innovative technologies into the wind turbine design
- Design lighter wind turbine blades of typical length for tower 150-200% larger than current wind turbines
- Design a turbine tower that is structurally sound at higher altitudes
- Construct a scaled prototype of turbine design for testing

D. Constraints

The sponsor wants the students to utilize new technologies and ideas in their design of the wind turbine. The new structural/mechanical designs have to be structurally sound at the height of 120 to 160 meters. In order for the turbine to be a realistic option for the southeast the design must be cost competitive with current wind turbines in the market. Along with being financially competitive, the turbine must be able to generate at least the same electrical power as current turbines. All of these initial designs and prototyping by the team must be accomplished before the end of the spring semester within a budget of $2,000. The design and performance specifications for the project are below.

E. Design Specifications

The design specifications for this project are as follows

- The wind turbine will be 150-200% taller than current wind turbines
- Must withstand stress of wind at 150m in SE United States
- The structure must support its own weight
- Blades will be lighter than average current turbines
- The designed wind turbine will be innovative in the wind energy field

F. Performance Specification

The performance specifications for this project are as follows

- Operating in all weather conditions with exception of winds >20 m/s
- There will be no energy used or fuel consumed
- The efficiency will be within a range of 30-35%

VI. Design and Analysis

This section displays the various designs created by the team and goes through the analysis of each of the designs to select the optimal design.

A. Functional Analysis

The components of the wind turbine that the team is working on are the blades of the wind turbine and the tower. There will be three blades with a length of 60 meters each and the tower will be 160 meters in height. The blades will be attached to a rotor that spins a 5 MW generator that will be used to generate electricity. A series of cables will transfer the generated power from the top of the wind turbine to the ground.

B. Bracing Beam Design

All designs can be seen in Appendix B.

B.1 Original Blade Design

After researching, the group decided to use the standard airfoil blade shell design. The airfoil is the optimum shape for gaining lift which will be essential for generating the most power. The material of the blades are still to be determined. Some of the materials considered are carbon fiber, Kevlar, and other composite fabrics. Inside the shell, a shear web is placed to strengthen the blades. The standard shear web is composed of one or two I-beams. The team came up with three designs originally for the wind turbine blade bracing beam that were aimed at reducing weight while still supporting the forces on the turbine blade. After the three designs were compared a fourth design for the bracing beam was developed and the new design was compared to the internal cylinder design which was the best design of the original three. The three original designs and the fourth final design along with descriptions of each are shown below.

The internal cylinder design, shown in Figure 3, consists of a standard airfoil turbine blade, internally supported by a hollow cylinder. The idea behind this design is that the hollow support will reduce the amount of

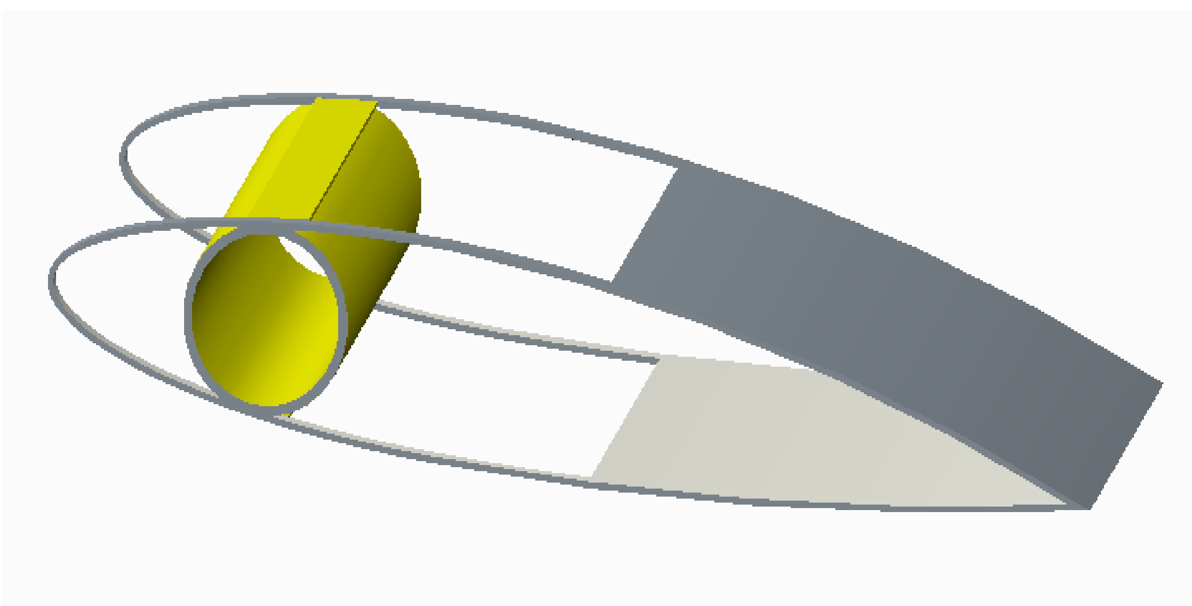


Figure 3. Blade Design Concept 1 (Internal Cylinder)

material in the blade, thus reducing the overall blade weight, while still maintaining strength. It was found that this design would be great at supporting the load, but would result in a very heavy bracing beam so it was removed as an option. The cylinder bracing beam also did not function very well in bending, which is the main load that the bracing beam faces. This design was selected as the best design of the original designs and it was compared to the new fourth design shown in Figure 4.

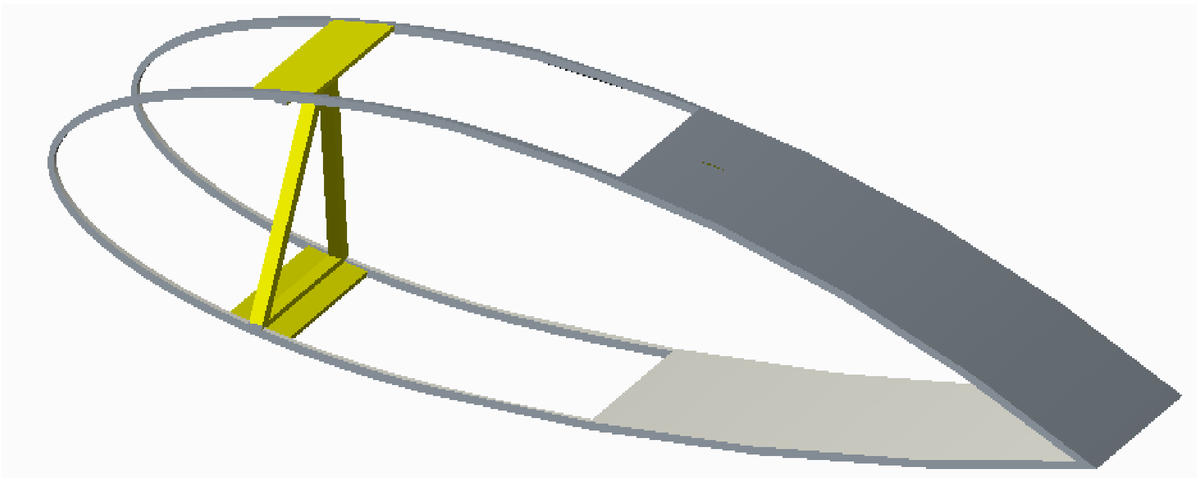


Figure 4. Blade Design Concept 2 (Internal Truss)

The internal truss blade turbine blade design shown in Figure 4 uses triangular trusses for the shear web. This design eliminates much of the material used. Triangles were chosen in this design because they distribute the compressive load uniformly. This design hopes to significantly reduce the mass while providing enough support so the blades do not bend. This design was very good at reducing the total material used as the bracing beam for the turbine blade, but the truss structure means that during construction the beam would have many points of bonding between the shear web and bracing truss. It was decided that the connections contain too many points of failure for the bracing beam. Because the blade cannot be opened and fixed after construction it was decided to go for a design that was more reliable even if more material was required.

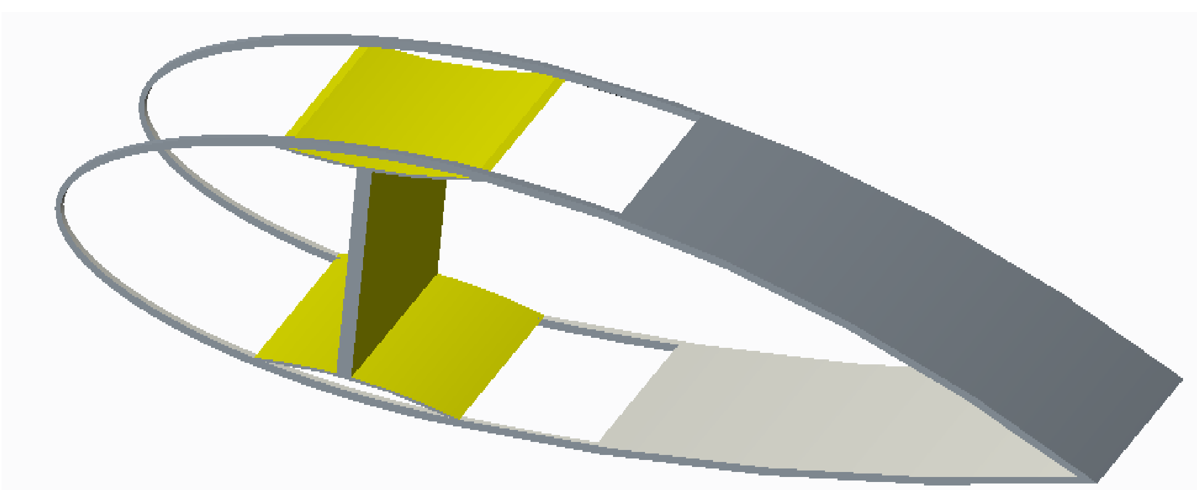


Figure 5. Blade Design Concept 3 (Single Post)

Figure 5 shows a design that uses a central I-beam placed in between two curved domes. To prevent the load from being too great on a single point in the blade, the top and bottom of the beam will sit on two curved surfaces which will attach to the top and bottom inner surface of the blade. The curved surface will take the point load from the central I-beam and distribute it over a larger area to prevent damage to the blade. As the dome size increases, the load decreases on the contact points and the shape of the dome will resist flattening out even if the load becomes too large. This design was very innovative which was requested by our sponsor, but the central I-beam posed a problem because it has to support the entire load along a single line on the domes. This means that if the connection between the beam and curved domes is severed, the entire bracing beam will fail. Also, the curved surfaces are difficult to fabricate which means that the beam will increase costs and production time for new turbine blades.

B.2 New Blade Design

The new bracing beam for the blade was developed after speaking to the sponsor. It is shown in Figure 6. The entire blade for the turbine can also be seen in Appendix B, along with the blades assembled onto the tower to complete the turbine.

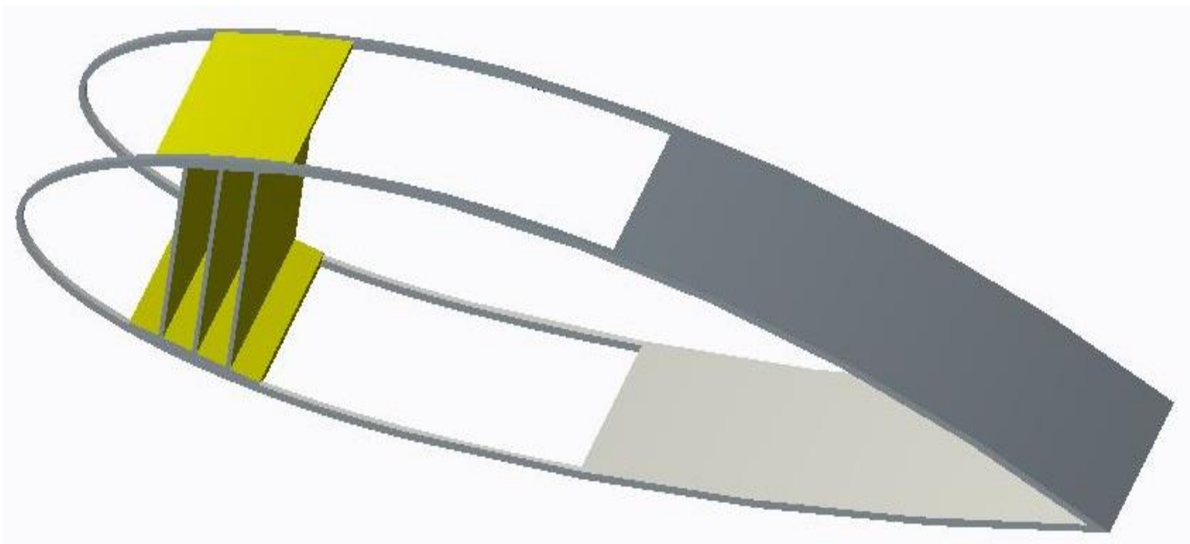


Figure 6. Blade Design Concept 4 (Triple Post)

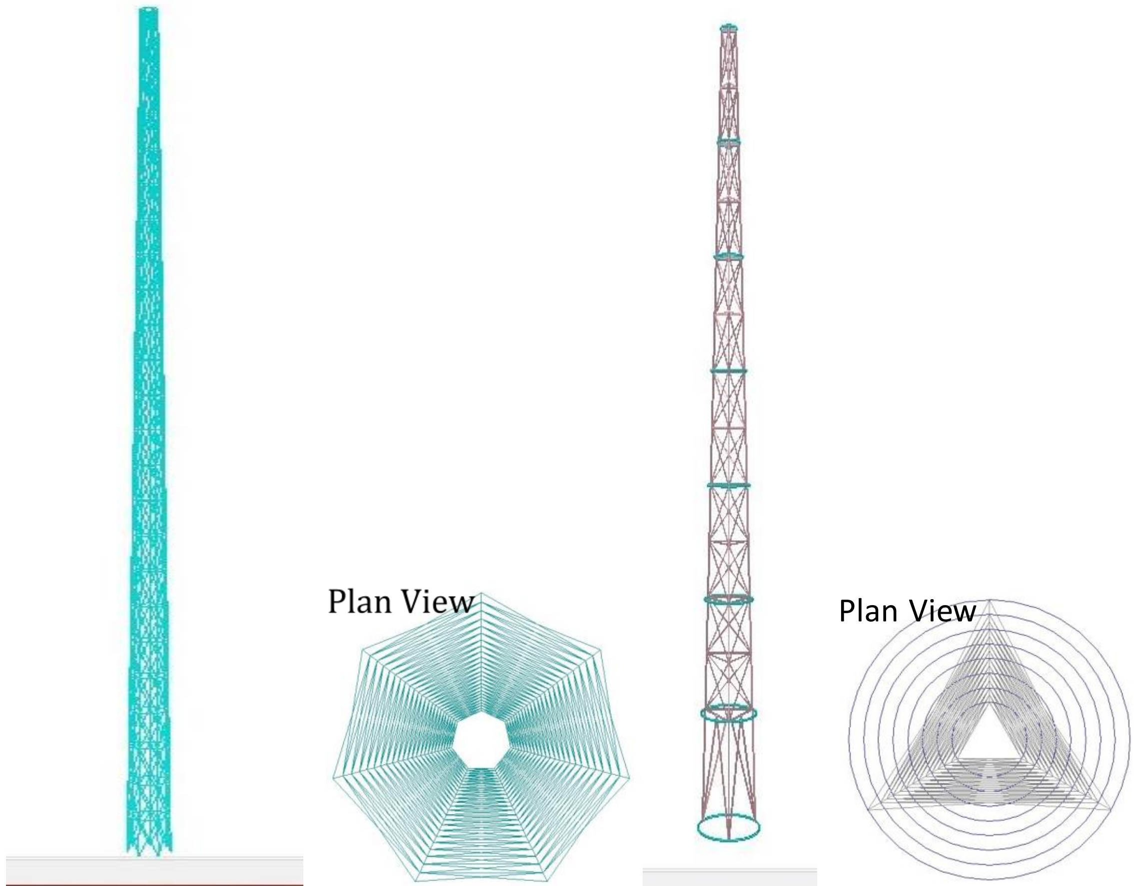
This design features a shear web that is supported by three posts that are evenly distributed across the shear web. The triple I-beam design means that the bracing beam will be able to handle large bending loads due to the wind force on the beam. By distributing the three posts over the surface the load is not placed upon a single line like the single post or truss design and this bracing beam can be easily produced because there are no complicated shapes to the design and the three posts means that if one post was to fail, the other two could still support the bending load. These mean that the bracing beam can use less material to support the same load which means less material can be used.

C. Structure Design

All designs can be seen in Appendix B.

C.1 Original Structure Design

This project requires designing a structure that is between 120-160 meters tall. Additionally, the structure must be able to support a nacelle of a 5MW wind turbine. Some of the main design challenges involve cost and transportation. Originally, the materials that were considered included concrete and steel. However, after comparing the two materials, the team decided that steel would be more efficient due to its high strength-to-weight ratio and ability to be fabricated offsite. However, unlike the typical tubular wind turbine towers, our team's designs feature a lattice structure. The steel lattice design minimizes the amount of material used while maintaining the strength of the tower.



Figures 7. Tower Design Concept 1 (Heptagonal Lattice) and 8. Concept 2 (Triangular Lattice)

The two initial designs rely on using the steel lattice structure that is wrapped in architectural fabric. This will result in a lighter structure and reduce the overall cost of materials.

The first design, shown in Figure 7, includes seven sides while the second design, shown in Figure 8, includes three sides. The number of sides used in the final design will depend on the transportability of the sections and stability of the overall tower. A three-sided tower has the appeal of having fewer members to assemble, with each span having four less sides than a seven-sided tower. However, there was very little difference in required material. In fact, the seven-sided tower uses a little less material because of geometric efficiency for a turbine that is to rotate a full 360 degrees. Furthermore, our seven-sided tower allowed the spans to be pre-assembled and transported as completed tubular sections, pre-wrapped with architectural fabric.

Furthermore, the three-sided tower uses tubular rings to aid in the ease of construction and to allow for the fabric to surround the structure, creating a cylindrical outer surface. The seven-sided tower does not require this function because the seven sides will encounter much less push force due to wind loading than three wider sides would feel.

Overall, we concluded that the seven-sided tower's benefits outweigh those of the three-sided tower both analytically in terms of strength and logistically in terms of transportation and construction costs.

Figure 9 shows the most common design used for 80-meter wind turbine towers. It is a steel tubular structure that is built by stacking multiple cylindrical cross sections on top of each other. The tower has a larger diameter at the base to improve stability. This tower is effective for use at 80 meters and below but it becomes less cost effective if built to taller heights. If this design is made for the project constraint of 120-160 meters the base will have to be larger and this could affect the transportability of the cylindrical sections. This tower is useful as a good baseline to measure the team's designs against. This type of tower design obviously uses more material than the lattice structures, but we have to test to see if the tube design is also more stable.

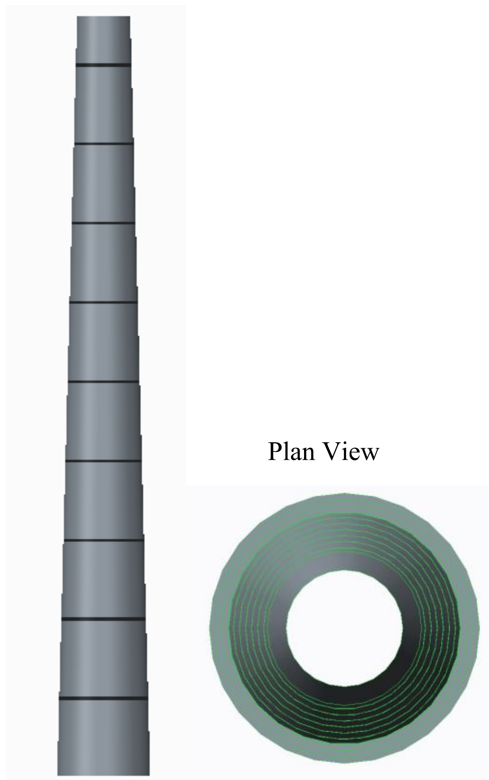


Figure 9. Tower Design Concept 3 (Steel Tube)

C.2 New Structure Design

The final tower design merges ideas from both preliminary designs. The new design consists of a seven-sided steel lattice tower with horizontal bracing and wrapped in an architectural fabric. The lattice structure reduces the overall amount of material required compared to a tubular structure. Additionally, the new design consists of a wider base. Even though widening the base requires on site assembly, the additional strength made this design more favorable. Moreover, tower lighting required by the Federal Aviation Administration and a ladder for maintenance use will easily be attached to the tower. Increased space within the tower will also provide the potential for bracing/guy cables in the future.

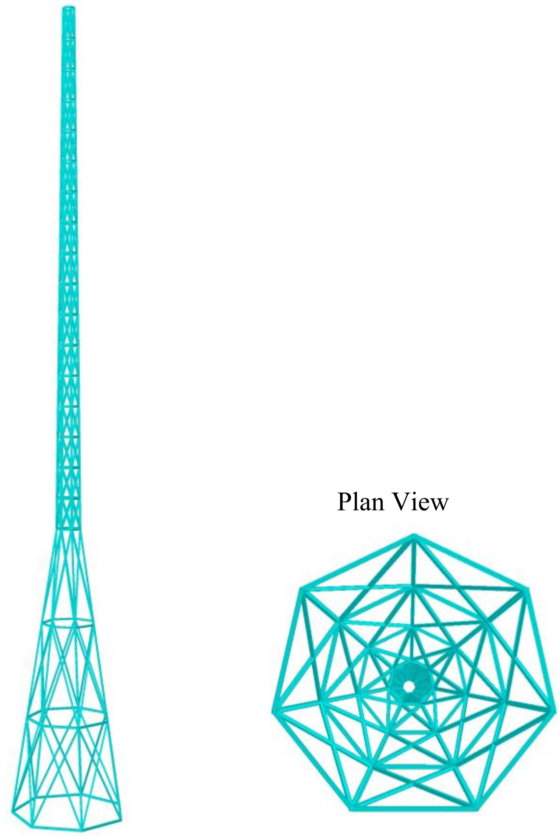


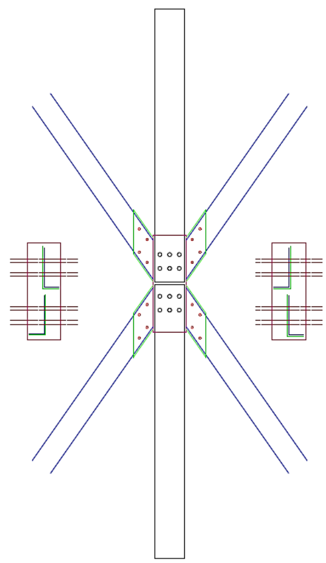
Figure 10. Tower Design Concept 4 (Tapered Heptagonal Lattice)

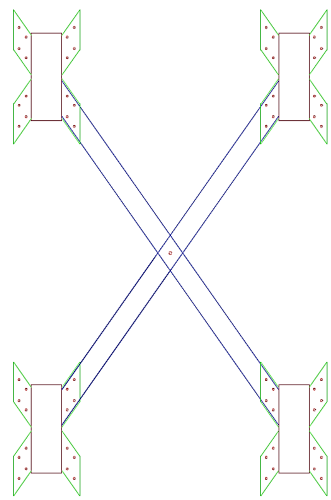
The tower consists of 20 vertical spans with three of those spans making up the base. As seen in Figure 10, the three base sections resemble a heptagonal pyramid, while the upper sections resemble a tubular shape. The main drawback of the tower design will be the increased size of the base. The base was designed to be wider than the recommended values in order to account for the moment within the structure. This wider base and horizontal tilt of the structural members significantly reduce the moment making the tower less likely to rotate. Since the base sections have a width of 31.5 feet, they will be assembled on site to allow for easy transportation of the material. However, this greatly increases construction time and costs. Meanwhile, the spans above the base will be pre-fabricated and pre-assembled and then transported to the site by standard freight trailers. The fabric may also be wrapped around each section prior to being transported to the site. A crane will be used to stack the sections on site. The reduced transportation costs and pre-assembly of the majority of the tower will offset a portion of the increased cost due to on-site assembly.

C.3 Tower Connections

The final design requires only one application of field welding. The connection between the wider base and more narrow upper sections will be under high stress due to forces applied by the blades on the tapered area. Therefore, this area must be welded to create a fixed connection. In addition to the one area of welding, other connections will be customized for this innovative design but are comparatively simplistic.

In order to connect the bracings to the channels, the bracing sections were designed to be channel shapes. The profile view of the bracing to column connection can be seen in Figure 11. Each pair of bracings will fit back-to-back with one member attaching to the inside half of the column and the other member attaching to the outside half of the column. This allows for a simple modular connection and will reduce the time of construction. The bracing will fit into larger angle shapes that are cut to match the angle of the incoming channel shapes. Currently, the columns are designed to be 16x16 inches, which restricts the channel braces to be a maximum of 7.5 inches in depth. This should not be a problem since the bracing must only resist axial forces. In addition, the bracings will be attached by a single bolt at the location where they cross. This will restrict the bracings from bending, but will allow the tower to rotate. This connection is shown in Figure 12.





Figures 11. Bracing-to-Column Connection and 12. Bracing-to-Bracing Connection

For the column-to-column connections, a square plug slightly wider than the columns will slide onto the outside of the column end allowing two columns to meet at the center of the plug. Then each of the columns will be bolted to the plug in two directions to account for the force of the blades in multiple directions. There will be two layers of bolts going in each direction and there should be no free space in between the plug and the columns after being bolted. This connection can be seen in Figure 13 where two sides of the columns are shown. The angles used for the connection of the bracings to the columns will be welded to the plug used in the column-to-column connections. This application of welding can be done off site.

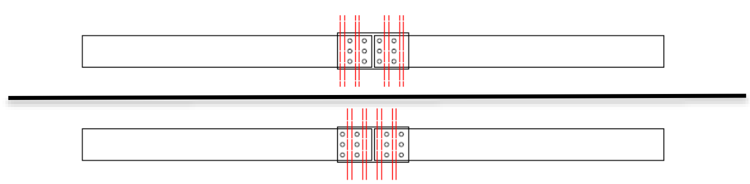


Figure 13. Column-to-Column Connection (Rotated 90 degrees)

The most complicated connection is located between the third and fourth sections from the ground. This is where the lower wider sections meet with the more narrow upper sections. Since the area is tapered, there will be high stresses located at this section. Therefore, this area will be welded onsite to maximize the strength of the connection. However, initially these sections will be connected using an additional “stirrup”. This stirrup will include the same male-to-female connections that were explained earlier. However, since the columns from the bottom are coming in at a significantly different angle from the columns on top, this connection must be customized for this special case. This connection is shown in Figure 14. The stirrup can be seen in the plan view, the columns connected to the stirrup can be seen in the elevation view, and a detailed elevation of one corner of the stirrup is also given to show the bolts required to keep the columns in place. The rectangular sections that the columns slide into will be welded onto the stirrup. Then the columns will be bolted into the rectangular sections in two directions to resist bending. This connection will be further analyzed to determine its effectiveness in our design.

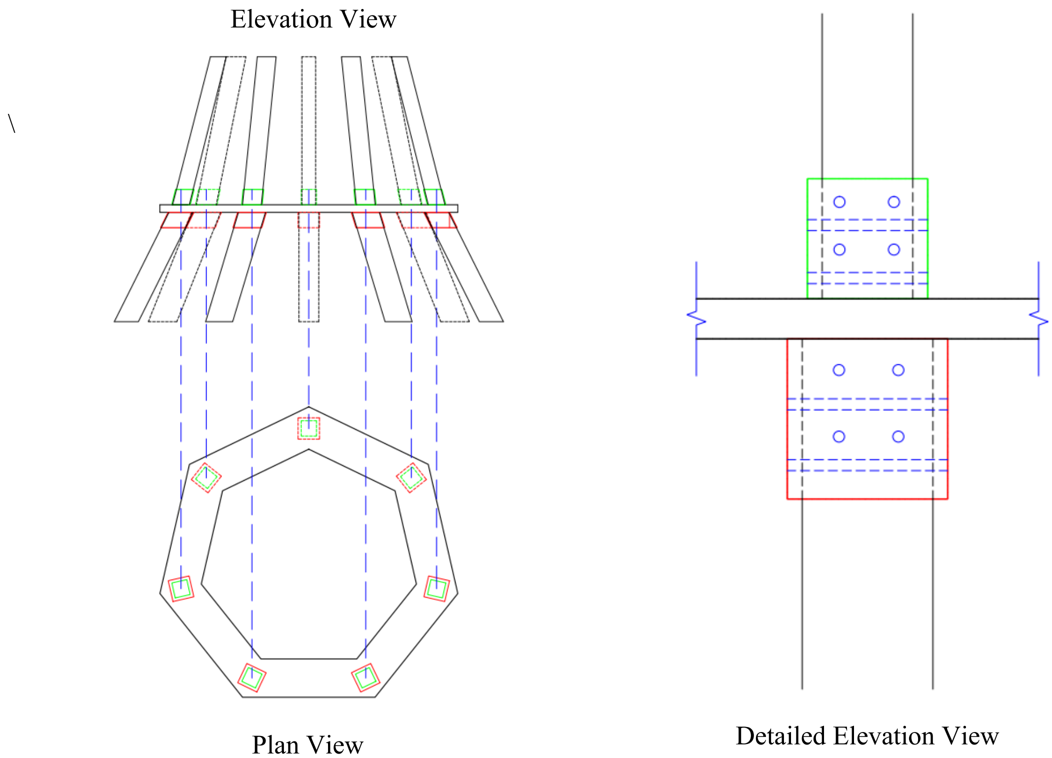


Figure 14. Column-to-Stirrup Connection

D. Evaluation of Designs

D.1 Blade Bracing Beam Analysis

There was a multi-step process used in selecting the best shape and material that will be used for the bracing beam in the 61.5m turbine blade. The bracing beam analysis was based upon the two bracing beams of the internal cylinder and triple post since the truss and single post beams were rejected earlier. The first step was to determine how the two beam designs reacted in bending and torsion, with bending being the most important since bending due to a wind load is the largest stress applied to the bracing beam. In order to determine how the beams reacted in bending and torsion, shape factor analysis was done. The shape factor shows how well a shape will withstand a bending or a torsional load. The higher a shape factor of a shape is the better it functions in that method of loading. For the two bracing beams the shape factors were compared in elastic bending and elastic torsion. The equations for the internal cylinder are

$$\varphi_{B:Cylinder} = \frac{3}{\pi} \cdot \frac{r}{t} \tag{1}$$

$$\varphi_{T:Cylinder} = 1.14 \frac{r}{t} \tag{2}$$

where, Equation 1 is for the bending cylinder and Equation 2 is for the cylinder in torsion, r is the outer radius of the cylinder, and t is equal to the wall thickness of the cylinder. The equations for the triple post beam are

$$\varphi_{B:Triple\ Post} = \frac{1}{2} \cdot \frac{h}{t} \cdot \frac{\left(1+\frac{3b}{h}\right)}{\left(1+\frac{b}{h}\right)^{1/2}} \tag{3}$$

$$\varphi_{T:Triple\ Post} = 1.19 \cdot \frac{t}{b} \cdot \frac{\left(1+\frac{4h}{b}\right)}{\left(1+\frac{h}{b}\right)^{2}} \tag{4}$$

where, h is the height of the bracing beam, b is the width of the top and bottom base, and t is the thickness of the top and bottom base and one-third the thickness of the three inner posts. To solve for the shape factor of both shapes accurately they have to have the same cross sectional area. The height, base, and thickness of the triple post beam were set and using Mathcad the thickness and radius of a cylinder were solved for. This can be seen in Appendix C. The results for the shape factor of the two beams are shown below in Table 1.

Table 1. Shape Factor Analysis of Bracing Beams

Bracing Beam	Elastic Bending	Elastic Torsion
Internal Cylinder	8.531	0.104
Triple Post	22.553	10.185

As can be seen above in Table 1, the triple post bracing beam performs almost 4 times as well in bending but about 100 times worse in torsion. Bending is by far the dominant load placed upon the bracing beam and torsion is mostly at the root of the wind turbine blade.

The second step to the bracing beam analysis was to calculate the forces on the bracing beam and then solve for the proper amount of material needed to withstand the load without fracturing. Once the minimum thickness for each bracing beam was found, the mass could be calculated. The wind load is based upon the wind speed blowing on the turbine. Data for wind speeds was only available at 80m so the team had to extrapolate the wind speed to a height of 160m. The average wind speed was found to be 8.3m/s at 160m in Florida. A factor of safety of 2 was introduced to account for any stronger gusts. The force on the wind turbine blade was found by multiplying the wind pressure by the surface area on one half of the blade. The wind pressure equation is

$$P = 0.5\, \rho_{air} {v_{air}}^2 c_d \tag{5}$$

where, ρ is the density of air, v is the air velocity, and c_d is the coefficient of drag. The worst case scenario was solved for which was when the maximum amount of area is exposed to wind load. In this case the wind turbine was treated like a flat plank, giving it a coefficient of drag of 1.2. The found pressure on the wind turbine blade was 206 Pa. The force on the blade was found by multiplying the pressure by the surface area and was found to be 44.8kN.

With the force on the bracing beam calculated it became possible to solve for the thickness of the triple post beam and the internal cylinder. The thickness of the triple post beam is

$$t_{Triple\ Post} = \frac{F_{wind} L}{\sigma_y C\left(\frac{1}{3}h^2 + hb\right)} \tag{6}$$

where, F is the wind load of 44.8kN, L is the length along the wind turbine blade where the force was applied with a value of 30m, σ_y is the yield strength of the material, C is a constant of 1, h is the height of the beam of 0.375m, and b is the base width of the beam of 0.375m. The yield strength was dependent on the on the material chosen. The thickness for the internal cylinder is a function of the inner and outer radii and is

$$r_i = \left({r_o}^4 - \left(\frac{4F_{wind} L r_o}{\pi \sigma_y C}\right)\right) \tag{7}$$

where, F is the wind load, L is the 30m length of the centroid, r_o and r_i are the outer and inner radius, σ_y is the yield strength of the material, and C is a constant of 1.

Both the radius and thickness of the cylinder were a function of the yield strength of the material chosen so the next step was to choose the best materials for the situation. To do this the best materials were chosen using a material index for a beam in elastic deformation since all deflection on the bracing beam needs to be only elastic. The goal is to select a material that can withstand the deflection of a wind turbine blade while minimizing the mass of the beam. The material index for both of the bracing beams is

$$M = \frac{E}{\rho} \tag{8}$$

where, E is the Young's Modulus of the material and ρ is the density of the material. The material index can be graphed as a line on a material properties graph shown below in Figure 15. Maximizing the material index shows that the best materials for this situation are at the top left of the chart.

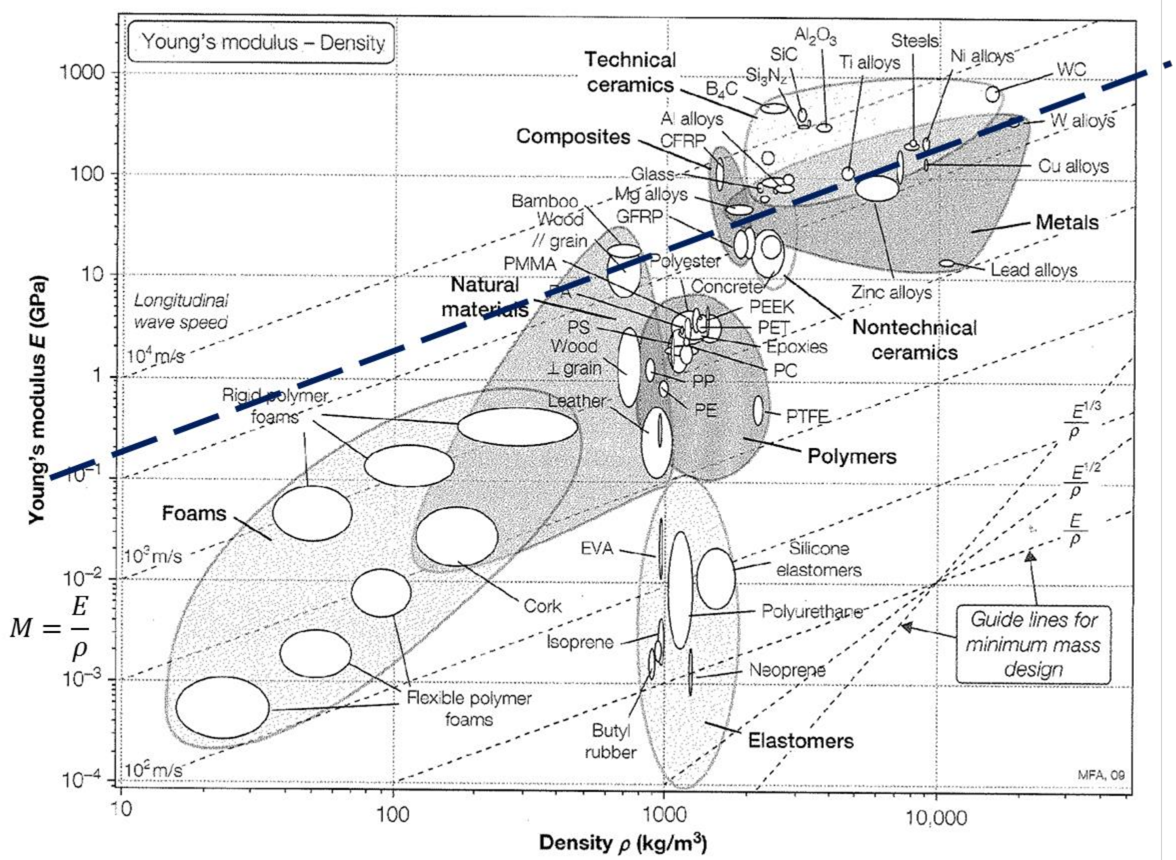


Figure 15. Young's Modulus versus Density Graph

Materials above the line are the best materials for the bracing beam. From Figure 15 it can be seen that the best materials for the bracing beams are steel, aluminum alloys, bamboo, and CFRP (carbon fiber reinforced polymer). These will be the materials chosen to calculate the thickness and radius of the cylinders. The materials, densities, yield strength, calculated thickness, and radius values are shown below in Table 2.

Table 2. Materials for Triple Post Bracing Beam

Material	Density(kg/m^3)	Yield Strength (MPa)	Triple Post Thickness (mm)	Internal Cylinder Inner Radius (mm)
Carbon Steel	7,800	322.5	22	125
Aluminum	2,700	265	27	71
Bamboo	700	39.5	181	>375
CFRP	1,550	800	0.9	170

From the table it can be seen that for the bamboo the inner radius for the cylinder is larger than the space available in the blade so it is removed as an option. CFRP has the smallest thickness and the smallest wall thickness for the internal cylinder, but with CFRP costing 30 times that of aluminum and 70 times the cost of steel it is also rejected. This leaves carbon steel and aluminum as possible options for the internal bracing beam. With these two materials the mass can be calculated using

$$m = \rho A_c L \tag{9}$$

where, ρ is the density of the material, L is the length of the bracing beam with a value of 61.5m and A_c is the cross sectional area of the bracing beam based upon the thickness and cylinder radius. The mass of the cylinder and triple post for both materials is shown in Table 3.

Table 3. Mass for Bracing Beams

Shape	Mass (Carbon Steel) (kg)	Mass (Aluminum) (kg)
Internal Cylinder	45,430	15,730
Triple Post	19,640	6,738

Table 3 above clearly shows that the internal cylinder has a much higher required mass to support the bending load than the mass of the triple post beam and then using aluminum as the material results in a mass of roughly one-third that of carbon steel. Since the triple post is also the best shape for use in bending the bracing beam will be a triple post beam made out of aluminum alloy with a thickness of 22mm and a mass of 6,738kg.

D.2 Blade Fabric Selection

The material selection for the shell of the wind turbine blades were designed with considerations of strength, stiffness, weight, and cost. To optimize these properties the shell will be constructed as a layered structure which will include the selected fabric(s), a resin, and a structural core. The layered structure will resemble Figure 16 below.

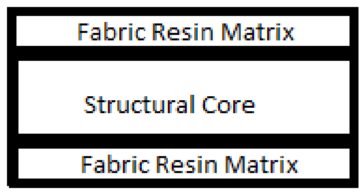


Figure 16: The layered structure of the external fabric design

Most of the blade shells in use today are made from E-glass fabrics, vinyl ester resin, and a PVC or balsa core. With technology continually improving, new materials have been created which will optimize the performance of the blade.

For fabrics, the shell will use mostly E-glass and carbon fiber reinforcements in high stress areas. The much lower cost of E-glass led to the decision for its use. Fabric orientations of mat, double bias, and unidirectional E-glass will be layered to improve the strength of the blade. Also, a unidirectional carbon fiber fabric will be applied in to reduce the weight while increasing the strength and stiffness. Since carbon fiber costs approximately 20 times more than E-glass it will be used sparingly.

Epoxy was selected as the resin for the shell of the blade. Compared to vinyl ester, epoxy has greater strength, stiffness, and fatigue strength while having at the same density. Epoxy generally costs more per kg, but with epoxy having greater strength than vinyl ester this requires less fabric which will reduce the blade weight and along with reducing the cost. Additionally, the epoxy will be pre-impregnated into a reinforcement fabric to further enhance the shell properties.

The core of the shell is used to help distribute the load and stresses on the outer fabric. For the core, styrene acrylonitrile foam (SAN) was selected. Key components that led to this decision was the good strength-to-weight ratio, stiffness-to-weight ratio, along with the high fatigue strength. Another feature of the material is the chemical stability which makes the core compatible with epoxy pre-impregnated. On the other hand, Poly Vinyl Chloride Foam (PVC) tends to have compatibility issues with resins and balsa has a much greater resin uptake which will increases the weight of the shell.

With growing industrial needs it is expected for higher quality materials to be more cost effective in future projects. For fabrics, chemically modified glass fibers such as S-glass may become prevalent in the industry with a decrease in price. Also the use of carbon fiber seems to be becoming more prevalent as well with more companies producing carbon fiber for industry. As for structural cores, there has recently been much development. One foam that may stand out in the future is Polyethylene Terephalate foam (PET). This foam is abundant, recyclable, and chemically stable. Since it has recently been introduced as a structural foam, the mechanical properties are lower than other options.

D.3 Tower Force Analysis

For design and analysis, we used Bentley's structural design and analysis software, STAAD Pro V8i. This is Finite Element Analysis (FEA) software where all of the members are modeled as single lines, connected by "nodes" or dots. Lines are designed to have a certain geometry and material properties (strength, cross-section, density, etc.)

and nodes are designed to have certain "fixity". The ground nodes may be designed as fully fixed, but other nodes may allow for slight rotation and are likely not fixed against any lateral translation (sway/movement). Additionally, individual members may be modeled as "truss members," which restricts their strength to purely axial forces (tension and compression). Connection design, therefore, must pay special attention to this aspect, as connections that allow for transfer of moment (male-female plugs or welds) cannot be used.

The forces that were input into STAAD Pro V8i were due to the self-weight of the structure, the self-weight of the turbine nacelle and blades, and the thrust. The self-weight of the structure was found to be approximately 650 tons. A standard nacelle combined with the blades came out to about 300 tons. However, the thrust had to be calculated using a series of equations. First, the mass flow rate had to be calculated using

$$\dot{m} = \rho * V_{wind} * A_{surface} \tag{10}$$

where, $\dot{m}$ is the mass flow rate, ρ is the air density, V_{wind} is the velocity of the wind, and $A_{surface}$ is the surface area on which the wind is acting (in this case, the swept area of the blades). The mass flow rate is then used to find the thrust by

$$F_r = \dot{m}(V_2 - V_1) \tag{11}$$

where, F_r is the thrust, V_1 is the velocity of the wind acting on the blades, and V_2 is the exit velocity of the wind past the blades. V_2 can be represented as a function of V_1 using

$$V_2 = V_1\sqrt{1 - \eta_{turbine}} \tag{12}$$

where, $\eta_{turbine}$ is the efficiency of the turbine. Moreover, the turbine efficiency can be calculated using the formula

$$\eta = \frac{W_{acting}}{W_{max}} \tag{13}$$

where, W_{acting} is the power at which the turbine is operating and W_{max} is the maximum power output based on the mass flow rate and the wind velocity. For the purposes of this analysis, W_{acting} is set to 5MW since this is the maximum power output expected from the selected generator and it will yield the maximum thrust value that will act on the tower. However, W_{max} must be calculated using the formula

$$W_{max} = \dot{m}\left(\frac{V_1^2}{2}\right) \tag{14}$$

An estimated wind speed of 11.4 m/s acting on the blades was applied and the resulting thrust value was 623 kN. However, this value was increased to include a factor of safety. Therefore, 445 kN of force was modeled in the x- and y-directions for a total of 890 kN. This loading is not meant to necessarily model a real-life situation, but instead introduces non-typical stresses that model unexpected loading cases. These may include a single failed connection, which would distribute all of its forces to adjoining members, as well as a strong wind-load hitting at a corner, which may shake the tower side-to-side, potentially increasing stresses beyond those expected in a one-dimensional 623 kN thrust. Furthermore, after achieving successful analyses, a critical bracing member was removed from various sections to simulate total failure. In every case, with the exception of removing a critical bracing member from the tower's base, the tower remained standing even though some yield limits were reached. This is much more desirable than a total collapse, and serves as a secondary confirmation of the tower's safety.

Furthermore, bracing members were modeled as "truss members" whose strength is limited to only axial forces. As such, the vertical "column" members are forced to carry all of the moment. At the connection between the widened base and the tubular tower, one application of field welding has been modeled by fixing the joints but allowing for translation in the x- and y-directions. At the base of the tower, the nodes have been modeled as fixed. This is accurate as our base will be bolted to a concrete foundation; for an offshore or mono-pile (onshore) tower, the fixity would require a spring coefficient. Without the spring's "forgiveness", our tower will have to retain all of the moment within the structure. The difference is similar to the action of breaking a pencil when held in one's free hand vs. breaking the pencil when secured in a vice grip. Without the "give" of one's flesh and wrist, the pencil reaches its breaking point much faster. As such, our tower is modeled as the pencil bound by a vice grip.

It may be noted that no modeling was done to simulate the wind load on the rest of the structure, itself. Our sponsor, Dr. Jung, has advised us to neglect such forces, as they have never shown to govern over that of the thrust due to the blades. Furthermore, if we were to model these forces, our design would likely be far over-conservative, equating to an over-stiff structure that wastes material.

After running optimization and making most efficient use of all shapes, given the worst stressed member in each span, a final analysis was run. The software gave an output of 0 errors and 0 warnings, which goes to show that no members had failed. Additionally, over 80% of all members were stressed to 0.6 - 0.9 of the acceptable strength value. This serves as a Goldilocks' confirmation; the tower is not over-designed, it is not under-designed, it is just right.

D.4 Tower Cost Analysis

The hollow structural steel (HSS) shapes offer a great strength/weight ratio. The price of production is between 10-40% higher than that of W-shapes coming out to about $600-$900/ton. With approximately 650 tons of steel, all HSS shapes, we can expect our steel material to cost approximately $450,000. Our shop welding can be expected to cost up to $8,000-10,000 and our field welding costing a modest $1,000-$1,500. This was calculated using an estimated labor and overhead cost of $45/hr and a labor time of 10lbs/hr at an operating factor of 30%. Additionally, the architectural fabric used to wrap the outside of the structure should cost under $4,000 based on the surface area before any necessary alterations are made.

The specifics of the process of fabric application has not been fully worked out, but we expect to have more accurate numbers in the beginning of next semester that represents the cost of fabric manipulation/sewing as well as the cost of the additional hours of construction needed to wrap and seal the structure. As a result of these intricacies of the construction process, as well as our uncertainty in an accurate time of construction, we have withheld construction cost estimates until the spring semester.

Also, NREL has provided calculations to estimate transportation, foundation, and construction costs based on values of the blade, nacelle, structure height, etc. However, these numbers are for a steel tubular tower. So values will need to be 'normalized' to that of steel lattice tower. Additionally, number estimates found for radio and satellite towers are also likely non-representative. With our preliminary attempts to achieve some accurate values based on NREL equations we came up a foundation costing about $104,000.

VII. Criteria, Method

For the selection of the blade cost, weight, manufacturability, durability, and strength were considered. The weight and strength of the design were considered to be the most important criteria in the selection process with a weight factor of four. The weight was considered important since the team is designing a taller, lighter wind turbine and strength is important because the design cannot fail when wind loads are imposed upon it. The durability was given a weight factor of three because it is important that the blades do not degrade quickly in order for the design to be cost-effective. The cost and manufacturability were given a weight factor of two because they still play an important role in the design of the blades, but their impact on the final design is not as large.

The structural selection criteria were cost, portability, weight, manufacturability, and durability. Portability and weight were both given a weight factor of four because it is essential that the structure can be delivered to the site and the taller tower means that weight induced forces will be larger so reducing weight is of extreme importance. The durability was given a weight factor of three because it is important that the tower have an extended life to reduce replacement and maintenance costs. The cost and manufacturability were given a weight factor of two because the designs need to be cost competitive with current turbine towers and it is important that they can be produced easily.

VIII. Risk and Reliability Assessment

There are many risks present in the construction of a wind turbine. One major risk is associated with the transportation of the wind turbine. The turbine requires large amounts of steel for the tower as well as very long blades. A fatal car accident could result if the steel for the tower or the blades were to fall onto the highway during transportation. To reduce this risk, the material for the turbine will be securely fastened into the vehicle during transit. Also, since the tower will be able to be hauled in standard sized semi-trailers, instead of oversized trailers, this will also reduce the risk associated with the transportation.

Another risk specific to this turbine's design is the need for an onsite welder to weld the tower together at a point approximately 55 meters above ground. This is a dangerous task and if proper safety precautions are not taken could lead to very serious injury. In order to reduce the risk associated with the onsite welding of the tower, the worker will be properly harnessed to the tower. This will prevent the worker from falling off the tower if he were to slip while working.

In addition to risks associated with the construction of the wind turbine, there are also risks present resulting from possible failure of the turbine. One such risk is that of the possibility of the tower falling over. This would be a highly dangerous situation since the tower is approximately 160 meters tall. In order to prevent such a calamity the tower will be structurally sound with an appropriate factor of safety and a very strong foundation. An additional source of failure associated with the wind turbine is that of the blades failing. To prevent failure of the 60-meter long blades, the bracing beam of the blades will be a triple I-beam support made of aluminum 6061. The triple I-beam structure will have an appropriate factor of safety and will help distribute the load acting on the blade while the aluminum will be strong enough to prevent failure.

Furthermore since the tower will reach such large heights into the atmosphere, the wind turbine will have the risk of interrupting air traffic. To reduce these risks the turbine will be properly painted and lighted according to regulations and codes from the Federal Aviation Administration (FAA). In addition, the team will have to submit building plans and location of the turbine to the FAA whom will conduct an Aeronautical Survey. This survey will determine if the turbine will interfere with air traffic, and will not allow the tower to be constructed unless it is in a safe location, ultimately reducing the risk of air traffic interference.

IX. Procurement

The team has been given a $2,000 budget to build a small-scale prototype of the wind turbine. During the fall semester the team did not use any of their budget due to the fact that they were in the design process. In the spring semester the team plans to spend most of this money on the production of the prototype. As it is not realistic or financially plausible to construct a wind turbine true to size, the team plans to construct a small-scaled prototype in the spring semester. The prototype will be approximately eight feet tall with three foot long blades. The tower will be made of steel, which is the material selected for the actual turbine structure. The team plans to obtain donated steel from Cives Steel Company out of Thomasville, Georgia.

The prototype blades will be made out of Styrofoam and wrapped in a fabric. The team plans on ordering two-inch thick rectangular Styrofoam sheets that are 24 inches by 36 inches from StyroShapes, a foam provider out of Hunt Valley, Maryland. These sheets will cost $154.86 for a case of ten sheets. In order to make three scaled down prototype blades the team will need six sheets of Styrofoam; however, the team will purchase a total of ten sheets of foam to allow room for mistakes. The team plans on gluing multiple sheets of foam together and then hand carving the shape of the blade. Due to financial constraints, the blades will be hand carved rather than ordering them from a company who can supply an accurate blade model when provided with a CAD drawing. After hand carving the shape of the blades they will be wrapped in a fabric which is still to be determined. Fiberglass, Kevlar, and craft fabrics are all being considered for this application and the best material will be determined early in the spring semester. Price will play the largest role in the selection of fabric for the prototype. To secure and harden the selected fabric, an Epoxy resin will be purchased for and will cost approximately $200. An additional $200 will be budgeted for other costs such as tools, adhesives, and shipping costs.

Once the blades are complete they will be attached to the tower. The method of attachment is still to be determined. Additionally, the team is considering attaching a car alternator to the turbine, allowing the power generated to be used in a small application such as lighting up a light bulb. The team is also in communication with several modeling companies to possibly obtain an exact small-scale replica of a single blade in addition to the prototype, if this will allow the team to remain under budget. Table 4 provides a summary of the approximate prototype costs.

Table 4: Approximate Prototype Costs

Materials	**~Cost ($)**
Steel	0
Small-scale replica	700
Fabrics	400
Styrofoam	155
Epoxy Resin	200
Other	200
Total	**1655**

X. Communications

Communication has been an essential part in the project and has allowed the students to keep track of what everyone is working on and what still needs to be completed. Talking between the civil and mechanical students has allowed each group to focus on their tasks of designing the blades and the tower and make sure they work together in the final design. The students share a Dropbox folder, send regular emails, and send text messages to keep everyone up to date. The group also meets with Dr. Taira and Dr. Jung every other week to discuss progress on the project and what still needs to be done. Communications with the sponsor and advisor outside of the meetings are done through email or office visits. The group has gotten much better over the semester about keeping everyone updated.

XI. Conclusions

The goal of this project is to design a new wind turbine that is 150-200% larger that can be used in the Southeastern United States. If a turbine that makes wind power feasible for use in Florida is developed, there will be a huge new market for turbine producers to sell to. Preliminary research has been completed for the project and three designs for both the blades and the tower have been produced. All of the prospective designs have been created in CAD software. The final design for both the wind turbine blade and tower design has been selected and the team is working on comparing how the design compares to other wind turbine that are being used currently. The team is also finalizing where to purchase materials for the prototype that will be built in the spring semester. This project will bring innovation to the wind turbine industry that could have allow for new areas to generate power with wind turbines.

XII. Environmental and Safety Issues and Ethics

There are few environmental and safety concerns involved with this tower design. The main environmental concern is the tower disrupting the flight paths of birds in the area. There are several safety issues that have been or will be addressed before the end of the project. The tower and blades have been designed so that the can be transported to the work site without extra modification to current methods. Maintenance on the wind turbine can be performed through a central ladder that uses a harness line and multiple attachment points for extra safety. Materials will be obtained from trusted sources to ensure all ethical standards are kept. The project plans to have as minimal an impact on the environment as possible since the wind turbine is focused on generating clean electricity.

XIII. Future Plans

The plan for the spring semester is to finish the cost analysis of the turbine and compare to other common turbines used in the United States to see if the design is cost-effective. Once this is done the team will order the prototype materials that will be used to build the prototype. The prototype will evolve to make sure it matches the final design chosen by the group. As the blades and tower are combined into a single unit, compromises may have to be made in the design to make sure all pieces work best together.

XIV. Gantt Chart & Resources

A. Gantt Chart

The general strategy of the team is to split up the various tasks into distinct sections to make the workload more manageable. Although everyone has individual tasks the team will still meet weekly to ensure that progress is being maintained throughout the semester. The team will also meet every other week with the sponsor and faculty advisor to keep them updated and inquire about any issues encountered. The Gantt chart, which will describe how the project is broken down, can be seen in Appendix A.

B. Resources

The primary resources the group used in design was Pro Engineer, AutoCAD, and STAAD Pro V8i. Calculations were performed mainly in Mathcad and Pro Engineer. The team used online vendors to research materials that will be used for the prototype and also fabricators that may be used to make accurate models of the turbine blades based upon the price. The group also has access to the College of Engineering machine shop for any parts that require machining. A table of the tasks shown in Table 5 that will be allocated to each member of the team is shown below. This will change as the spring semester progresses.

Table 5. Allocation of Resources

Task	Team Member(s) Responsible
• Background Research ○ Wind Power	• All team members
• Background Research ○ Blade Shape (Airfoil)	• Abigail McCool • Steven Blanchette
• Background Research ○ Blade Material	• Jeremiah McCallister • David Delie
• Background Research ○ Structure (Design and Material)	• Kimberly Martinson • Theodore Meros
• Preliminary Blade Designs	• Jeremiah McCallister • Abigail McCool • Steven Blanchette
• Preliminary Structure Designs	• Kimberly Martinson • Theodore Meros
• Blade CAD Drawings	• Steven Blanchette
• Structure CAD Drawings	• Kimberly Martinson • Theodore Meros
• Blade Material Selection	• Jeremiah McCallister • David Delie
• Structure Material Selection	• Kimberly Martinson • Theodore Meros
• Force Analysis (Using NREL FAST)	• Jeremiah McCallister • Abigail McCool • Theodore Meros
• Cost Analysis	• David Delie • Kimberly Martinson
• Design Selection	• All team members

XV. References

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[5] "How Does a Wind Turbine Work?" *Energy.gov*. U.S. Department of Energy. Web. 22 Sept. 2014. <http://energy.gov/maps/how-does-wind-turbine-work>.

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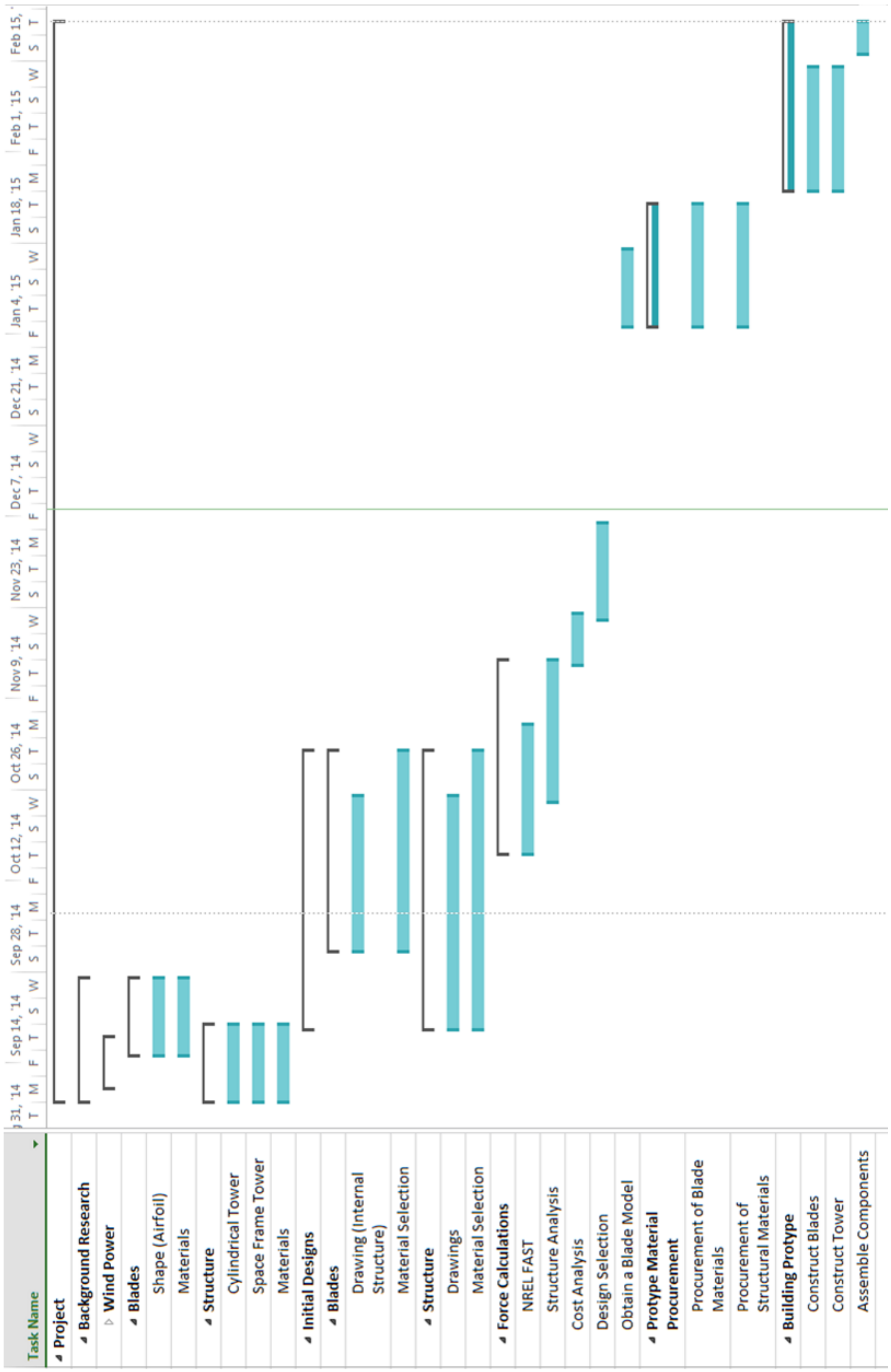
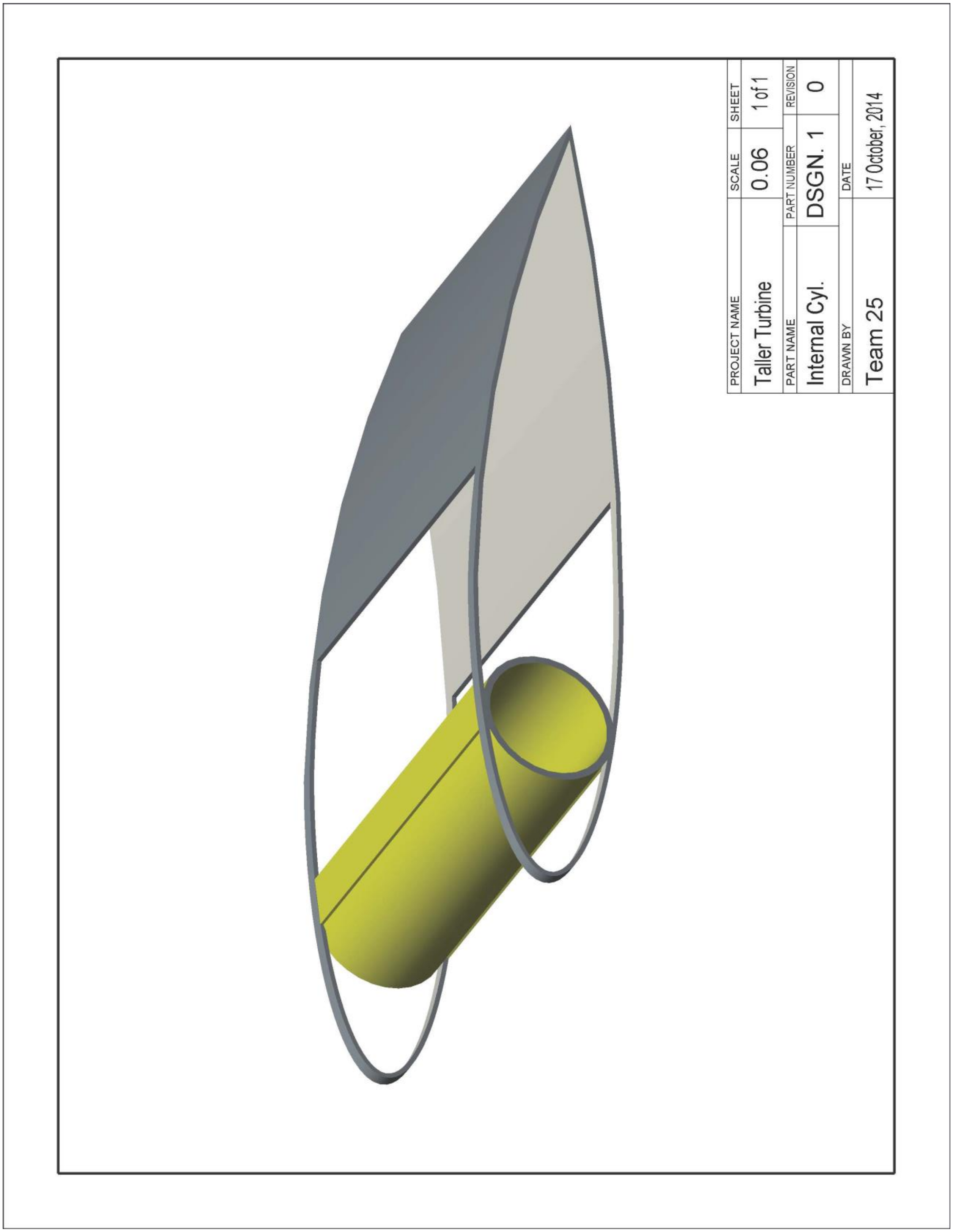
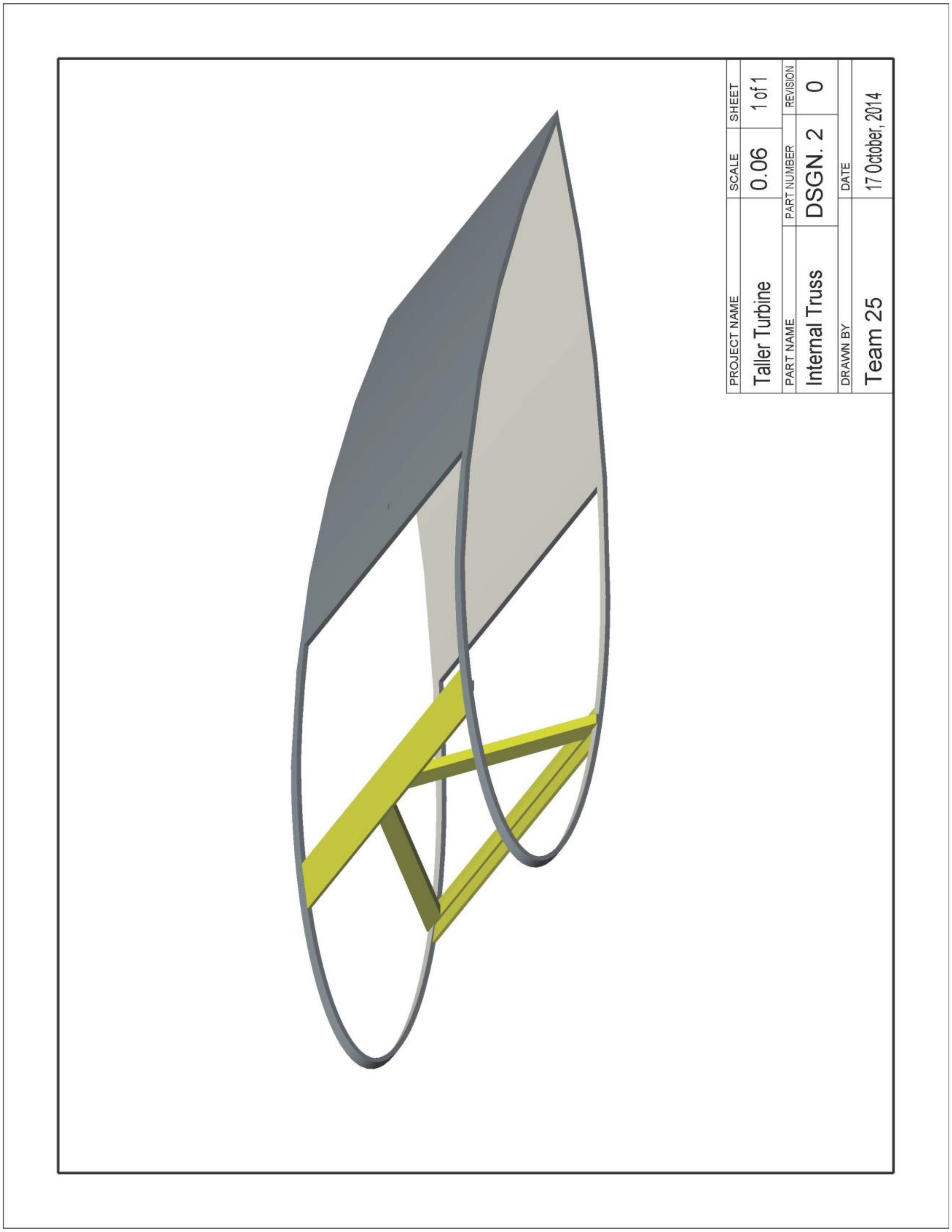
[7] "Energy Department Announces $2 Million to Support Manufacturing of Taller Wind Turbine Towers." *Energy.gov*. Office of Energy Efficiency & Renewable Energy, 18 Sept. 2014. Web. 22 Sept. 2014. http://www.energy.gov/eere/articles/energy-department-announces-2-million-support-manufacturing-taller-wind-turbine-towers

Appendix A: Gantt Chart



Appendix B: Design CAD

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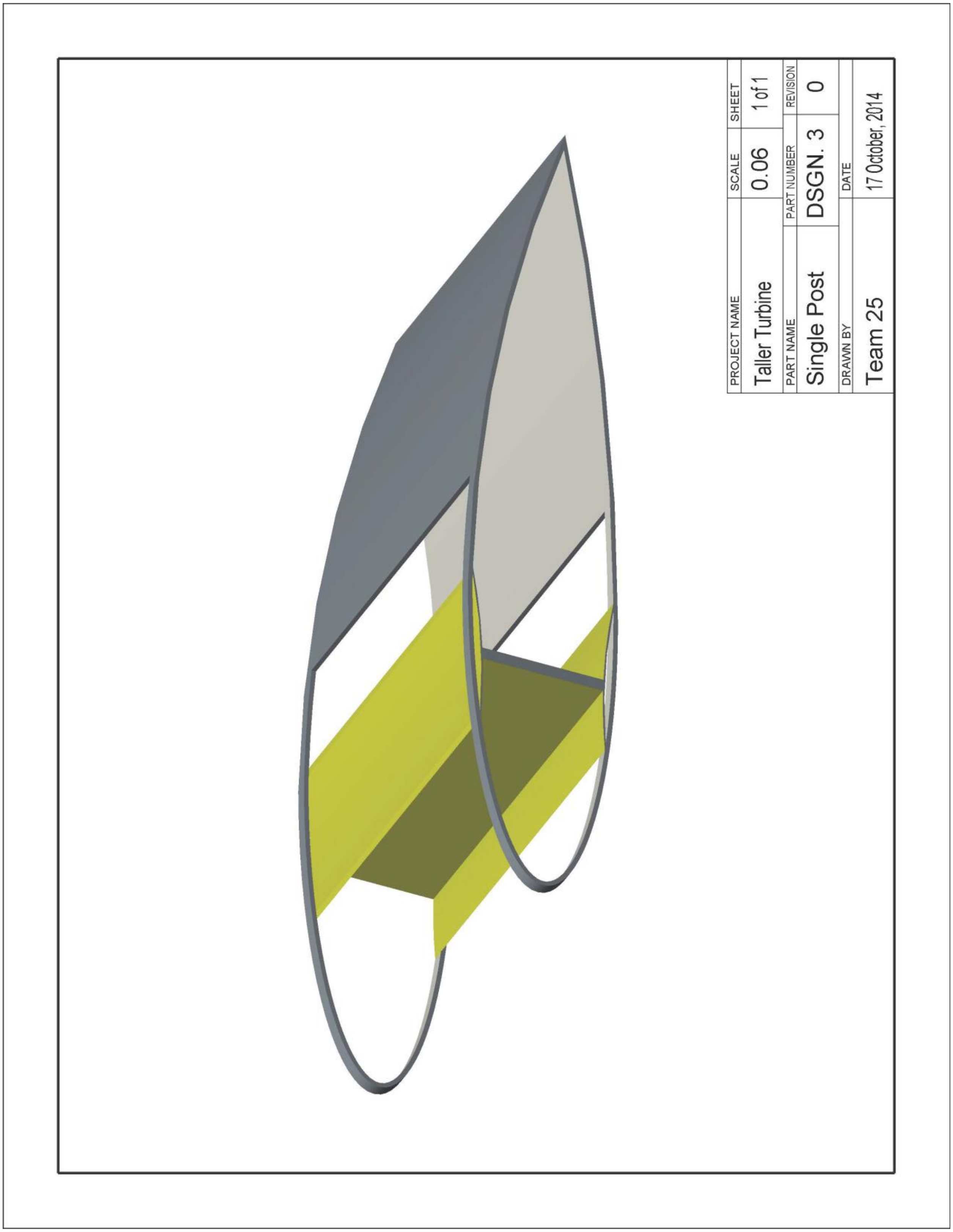
DRAWN BY
Team 25
DATE
17 October, 2014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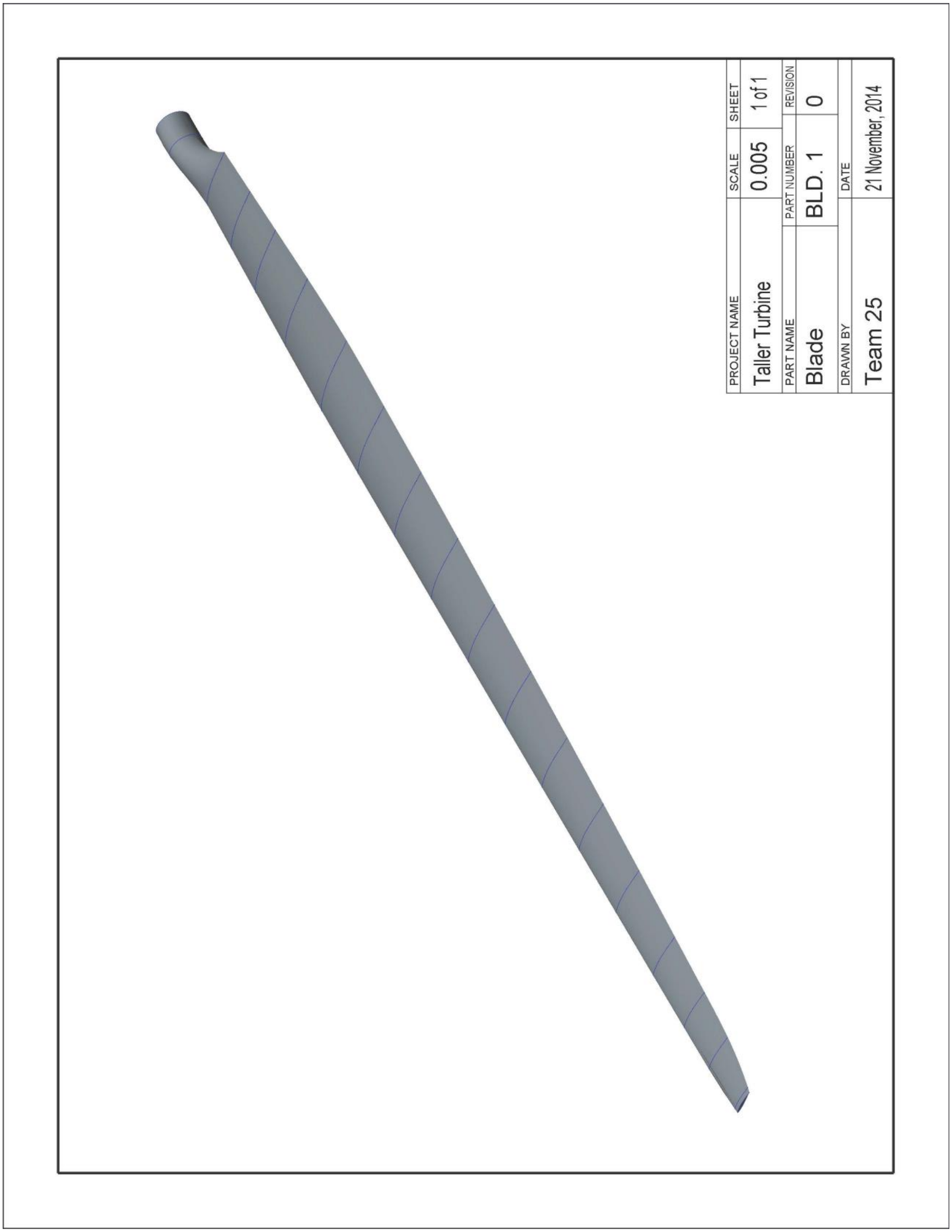
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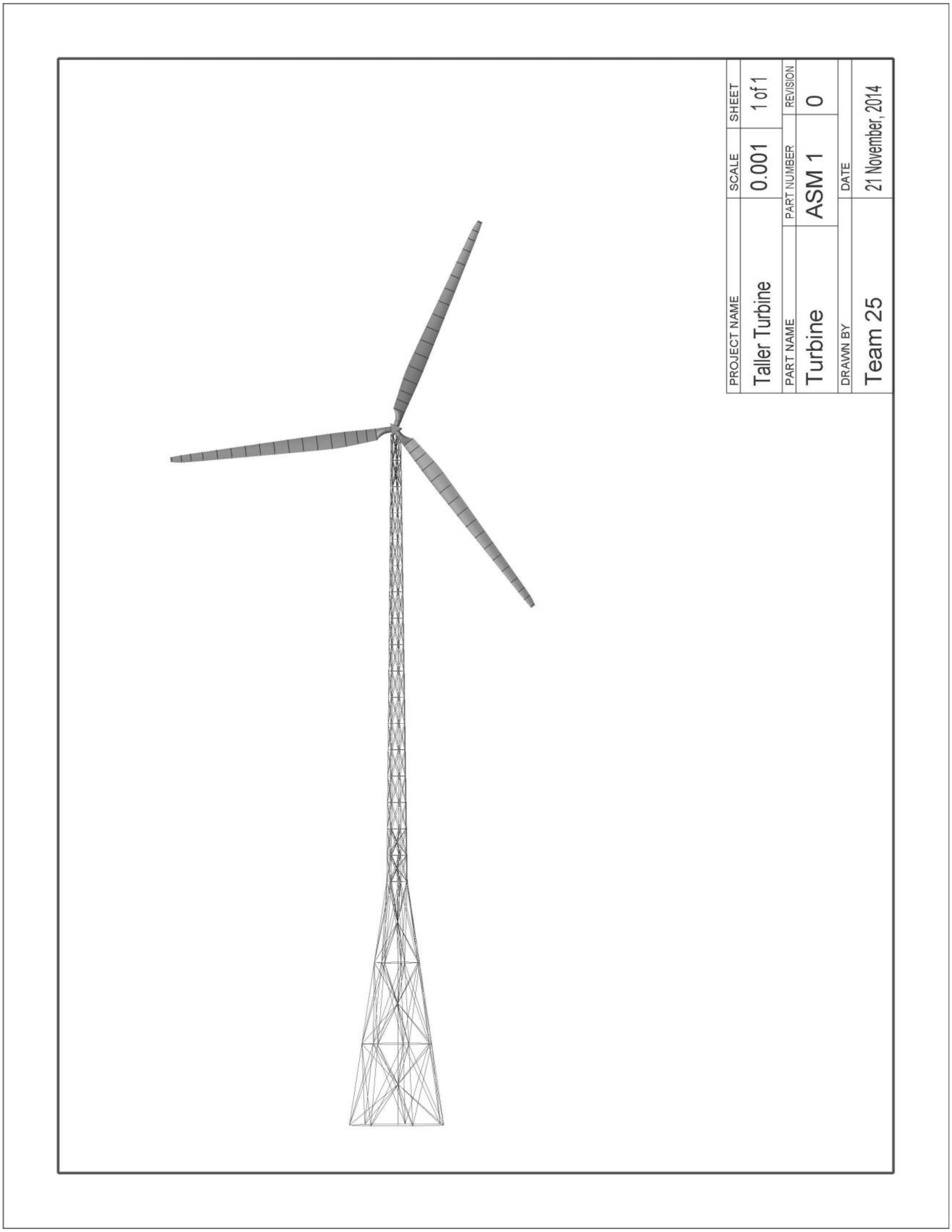
21 November, 2014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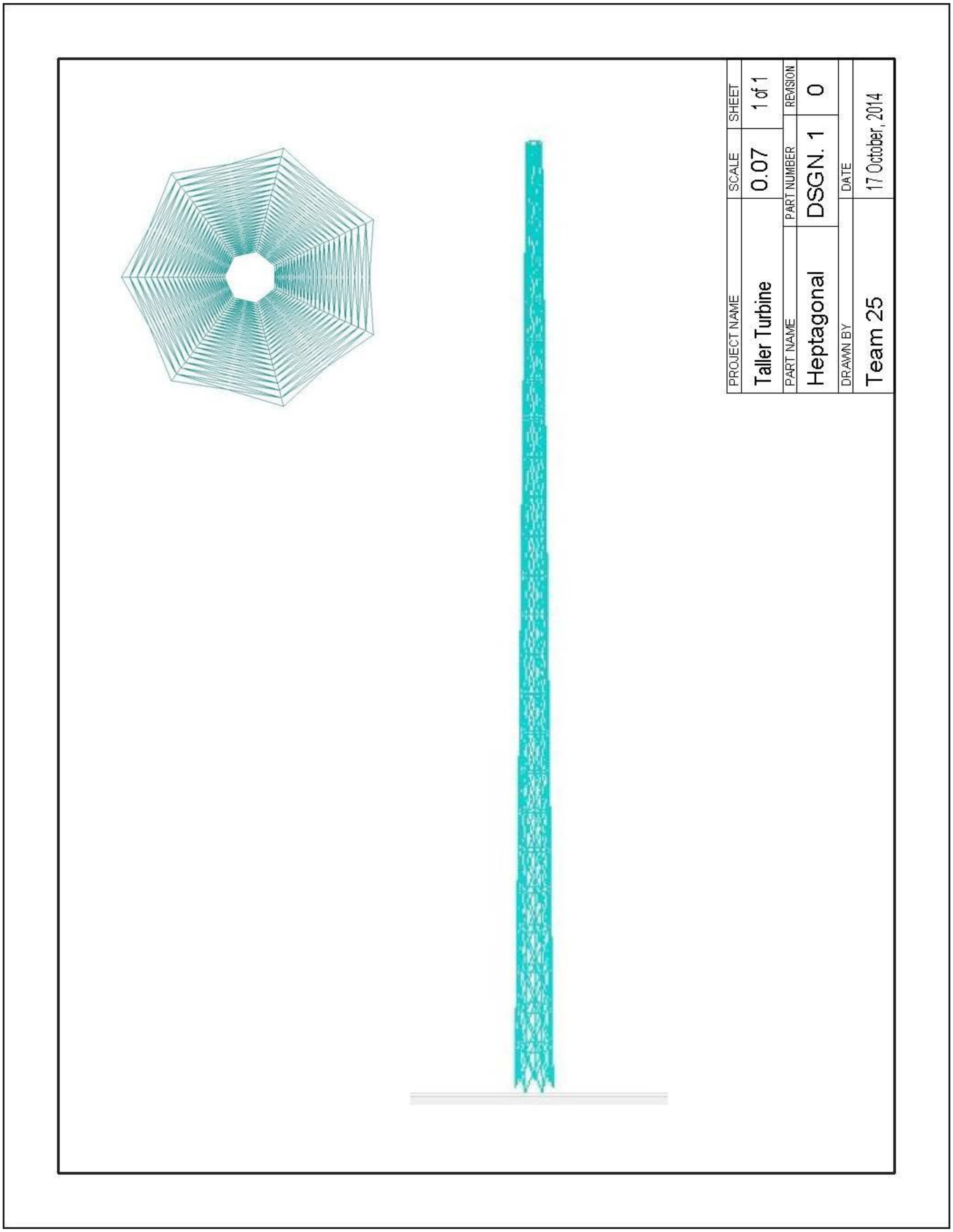
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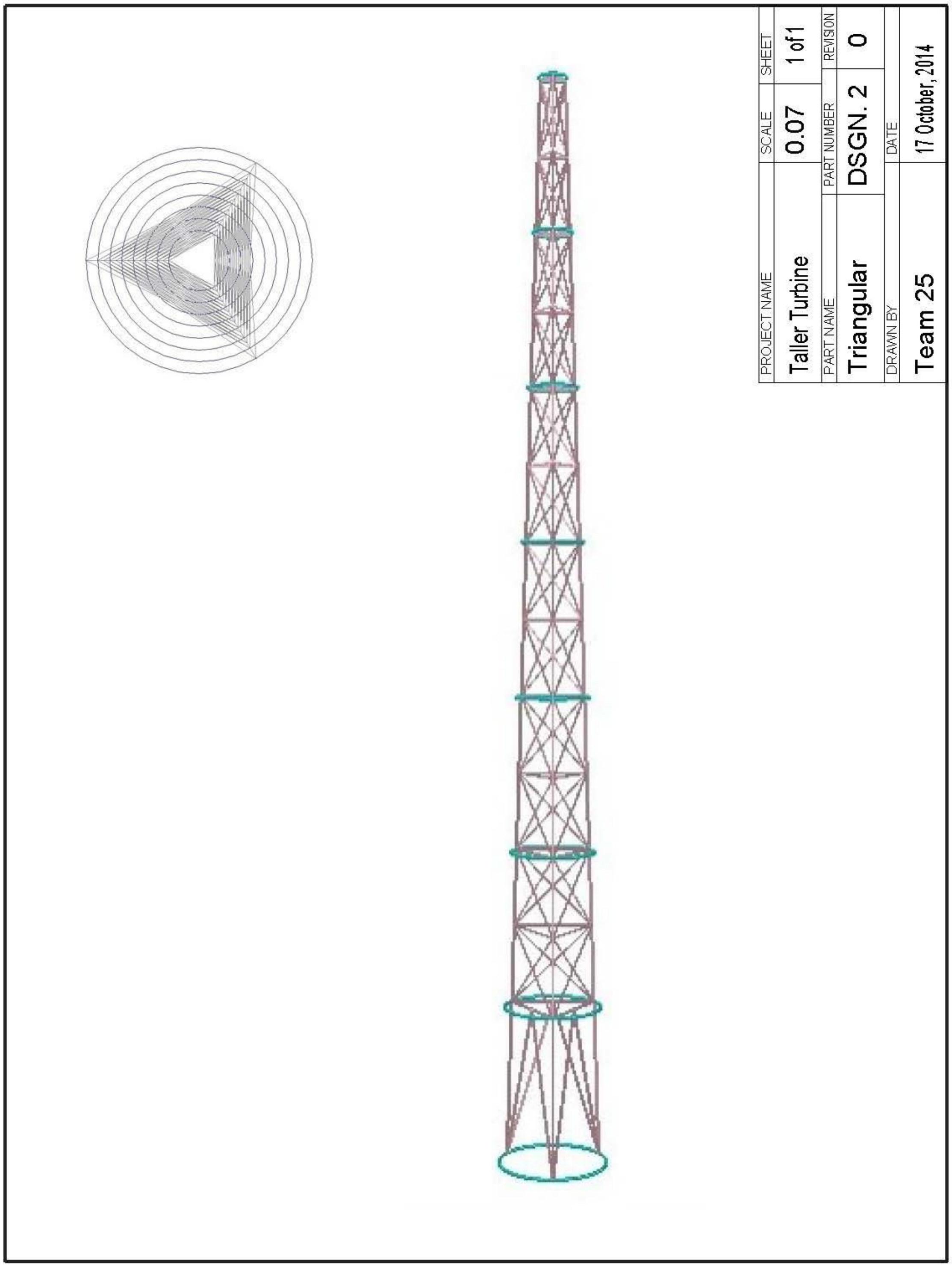
Team 25
DATE
17 October, 2014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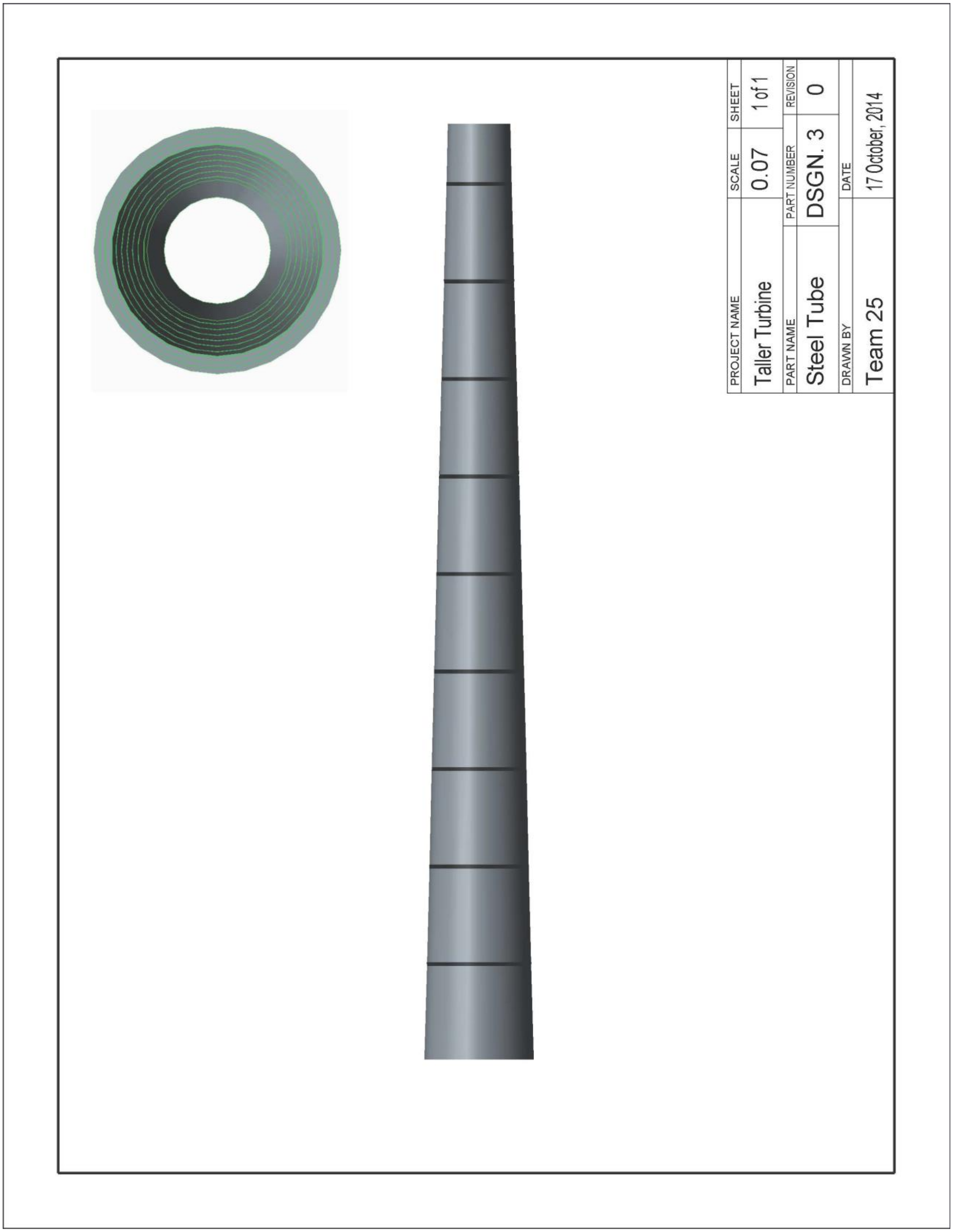
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SHEET
1 of 1
PART NUMBER
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REVISION
0
DATE
17 October, 2014

Appendix C: MathCad Anaylsis

Blade Analyis

$\rho_{air} := 1.25 \frac{kg}{m^3}$ $V_{air} := 16.6 \frac{m}{s}$ $C_d := 1.2$

$P := \left(\frac{1}{2}\right) \cdot \rho_{air} \cdot \left(V_{air}^2\right) \cdot C_d = 206.67 m^{-1} \cdot kg \cdot s^{-2}$

$SA := 433.58 m^2$

$Area1 := SA \cdot .5 = 216.79 m^2$

$F_f := Area1 \cdot P = 44.804 \cdot kN$

$r_o := 0.1875 m$

$Length_{centroid} := 30 m$

$C := 1$

$\sigma_y := 300 MPa$ A1

$$r_i := \left[r_o^4 - \left(\frac{F_f \cdot Length_{centroid} \cdot 4 \cdot r_o}{C \cdot \sigma_y \cdot \pi} \right) \right]^{\frac{1}{4}}$$

$r_i = 0.114\,m$

$$r_{avg} := \frac{(r_i + r_o)}{2} = 0.151\,m$$

For Aluminum

$\rho := 2700 \frac{kg}{m^3}$ $E := 75GPa$

$Length_{blade} := 61.5m$

$C_2 := 3$ constant dependent on how the blade is loaded

$\delta := 2.91m$ δ is deflection of the centroid solved based on tip deflection

$$mass := \rho \cdot Length_{centroid} \cdot \left(\frac{2F_f \cdot Length_{centroid}^3}{C_2 \cdot E \cdot \delta \cdot r_{avg}^2} \right)$$

$mass = 1.321 \times 10^4 kg$

Blade I-Beam Analyis

$\rho_{air} := 1.25\frac{kg}{m^3}$ $V_{air} := 16.6\frac{m}{s}$ $C_d := 1.2$

$P := \left(\frac{1}{2}\right) \cdot \rho_{air} \cdot \left(V_{air}{}^2\right) \cdot C_d = 206.67m^{-1} \cdot kg \cdot s^{-2}$

$SA := 433.58m^2$

$Area1 := SA \cdot .5 = 216.79m^2$

$F_f := Area1 \cdot P = 44.804 \cdot kN$

$h := .375m$

$b := 0.375m$

$Length_{centroid} := 30m$

$C := 1$

$\sigma_y := 300MPa$ Al

$$t := \frac{F_f \cdot Length_{centroid}}{\sigma_y \cdot C \cdot \left(\frac{1}{3}h^2 + h \cdot b\right)}$$

$t = 0.024\,m$

$t = 0.941 \cdot in$

$Length_{blade} := 61.5m$ $\rho := 2700 \frac{kg}{m^3}$

$volume := [2t \cdot (h + b) \cdot Length_{blade}] = 2.204\ m^3$

$mass_{brace} := volume \cdot \rho$

$mass_{brace} = 5.952 \times 10^3\ kg$

$weight_{brace} := mass_{brace} \cdot 2.2 \frac{lb}{kg}$

$weight_{brace} = 1.309 \times 10^4 \cdot lb$

$Volume_{shell} := 1.1043186m^3$

$\rho_{fiberglass} := 2580 \frac{kg}{m^3}$

$mass_{shell} := Volume_{shell} \cdot \rho_{fiberglass}$

$mass_{shell} = 2.849 \times 10^3 \cdot kg$

$weight_{shell} := mass_{shell} \cdot 2.2 \frac{lb}{kg}$

$weight_{shell} = 6.268 \times 10^3 \cdot lb$

$weight_{blade} := weight_{shell} + weight_{brace}$

$weight_{blade} = 1.936 \times 10^4 \cdot lb$

Clyinder Blade Analysis

$\rho_{air} := 1.25\frac{kg}{m^3}$ $V_{air} := 16.6\frac{m}{s}$ $C_d := 1.2$

$P := \left(\frac{1}{2}\right) \cdot \rho_{air} \cdot \left(V_{air}^2\right) \cdot C_d = 206.67 m^{-1} \cdot kg \cdot s^{-2}$

$SA := 433.58 m^2$

$Area1 := SA \cdot .5 = 216.79 m^2$

$F_f := Area1 \cdot P = 44.804 \cdot kN$

$r_o := 0.1875 m$

$Length_{centroid} := 30 m$

$C := 1$

$\sigma_y := 300 MPa$ Al

$$r_i := \left[r_o^4 - \left(\frac{F_f \cdot Length_{centroid} \cdot 4 \cdot r_o}{C \cdot \sigma_y \cdot \pi}\right)\right]^{\frac{1}{4}}$$

$r_i = 0.114\ m$

$r_{avg} := \frac{(r_i + r_o)}{2} = 0.151\ m$

$Length_{blade} := 61.5 m$ $\rho := 2700\frac{kg}{m^3}$

$volume := \left[\pi \cdot \left(r_o^2 - r_i^2\right) \cdot Length_{blade}\right] = 4.301\ m^3$

$mass_{brace} := volume \cdot \rho$

$mass_{brace} = 1.161 \times 10^4 kg$

$weight_{brace} := mass_{brace} \cdot 2.2\frac{lb}{kg}$

$weight_{brace} = 2.555 \times 10^4 \cdot lb$