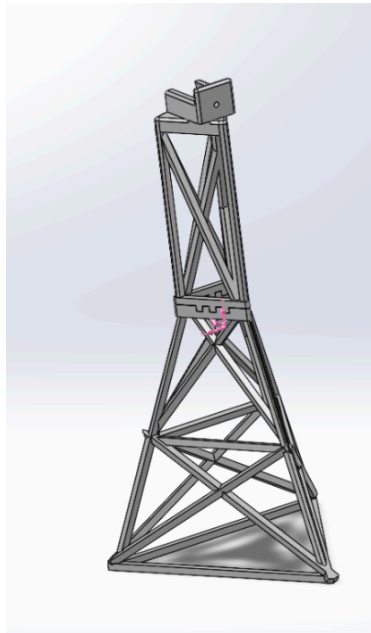




Maximizing Wind Energy Capture: Design, Analysis, and Testing of a Wind Turbine

by

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E26: Three-Dimensional Modeling for Design

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Project Summary:

As the second most utilized renewable energy source in the world, wind is an important resource in meeting the ever rising energy demands. Therefore, it is crucial to efficiently harness this renewable energy. This project aims to maximize wind energy capture of wind turbines while using minimal materials.

Our wind turbine consisted of three primary components: the rotor blade, turbine tower, and motor. We utilized a three-blade configuration for our rotor blade with each blade having length 2.5 inches. Our rotor blade also had a 13 degree angle of attack. The turbine tower, with a volume of 16.21 cubic inches, utilizes a truss structure design. Our design process began with basic sketches, which were transferred over to SolidWorks, where we designed 3D models for our wind turbine components. After completing our design, we conducted Finite Element Analysis (FEA) on our tower assembly. The simulation showed that with 5lbs of force applied to the motor housing, the tower experienced 1.817mm of displacement. Furthermore, the maximum stress on the tower was $7.712 \times 10^6 \text{ N/m}^2$. The minimum value for factor of safety was 5.8, which shows that the system is 5.8 times stronger than required for the load. After 3D printing our wind turbine components and assembly, our tower weighed in at 233 grams. Our wind turbine was then subjected to a series of tests to measure power output and structural integrity under load. The wind turbine achieved a maximum power output of 1.66 watts, and the deflection tests showed that the wind turbine experienced displacement ranging from 0.12 mm under a load of 0.981 N to 3.52 mm under a load of 29.3 N.

Overall, the wind turbine yielded good results in the testing phase. We met our objective of maximizing energy output while minimizing material used. However, upon reflection, there are some improvements that can be made. For instance, better alignment between tower segments and exploring an improved, rotor blade design might yield better results.

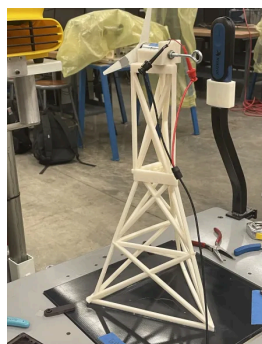


Figure i. Image of tower during testing phase

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1. Introduction

Among all energy sources used worldwide, wind energy is one of the most prevalent. According to Power Technology, “Wind is the second most widely used renewable energy source... accounting for approximately 24% of the world’s total renewable energy generation capacity.” Now, how exactly is this wind energy produced? The answer is simple: wind turbines. “Wind turbines installed in all 50 states supplying more than 10% of total U.S electricity and large percentages of most states’ energy needs” (WINDEXchange). Because of the constant rise in energy demands, our mission to create the most energy-efficient wind turbine is very vital to our daily life. Our goal in this class was to create a wind turbine that could generate the most energy possible while using the least amount of materials possible through design and 3D printing.

1.1 Structure of a Wind Turbine

In their simplest form, the rotor, main shaft, and generator are the three main parts of a horizontal wind turbine. The rotor has aerodynamically shaped blades and is frequently positioned high above the tower. These blades are designed to efficiently harness wind energy. As the wind blows at the blades, a lift is produced by the wind as it passes over the blades and as a result, they rotate. The generator spins as a result of the blades' rotational movement being transferred to the main shaft.

1.1.1 How a Wind Turbine Creates Energy

An engineering masterpiece is the wind turbine blade's aerodynamic design. The blades' optimal shape and angle guarantee maximum energy absorption. The pressure on one side of the blade drops when the wind blows, resulting in an imbalance in pressure that causes the blades to spin. This rotation is an essential phase in the energy generation process—the mechanical representation of wind energy being transformed into kinetic energy.

1.1.2 Energy Generation

The generator, which is usually placed behind the rotor, is the brains of a wind turbine. The generator is powered by the main shaft's rotation. Magnets inside the generator produce a magnetic field, which wire coils are carefully positioned inside of. By using the principles of electromagnetic induction, the magnetic field causes a flow of electrons in the wire coils as the shaft rotates, producing electricity. Alternating current (AC), which is the source of this electricity, is conditioned and converted into a standard voltage that may be used with the grid.

1.1.3 Increasing the Efficiency of Wind Turbines

Modern technologies are used by wind turbines to guarantee maximum efficiency. By allowing the turbine to spin horizontally, yaw control systems guarantee that the rotor is constantly pointed toward the wind. Pitch control systems modify the blades' angle to enable the turbine to run effectively at various wind speeds. Furthermore, real-time data is provided by sensors and weather monitoring equipment, which enables turbines to modify their operation and positioning in order to capture the most energy from the wind.

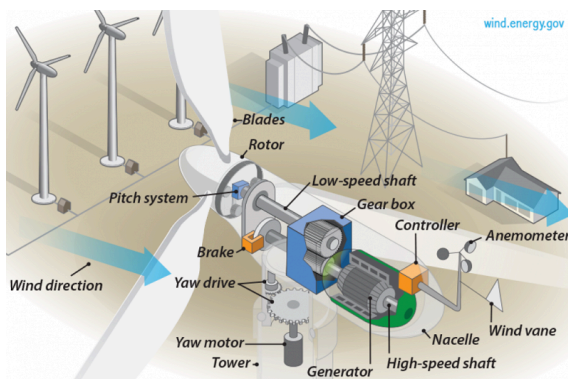


Figure 1.1 Parts of a Wind Turbine

1.2 Parts of a Wind Turbine

1.2.1 The Blade

An airfoil-shaped blade used in wind turbines harvests wind energy and transforms it into mechanical energy. The wind turbine's rotor, or the revolving component mounted atop the tower, is where the blades are fixed. The rotor spins because of the lift produced when the wind passes over the blades. A generator is attached to the rotor, and it is the generator that transforms mechanical energy into electrical energy. Effective blades are reliant on three main components:

1) Blade Profile: The blade profile data represents a blade's geometric and structural characteristics. These profiles are independent of the way the length is segmented and broken into portions at several discrete arc lengths along the blade length. Curved profiles are typically the most advantageous Blade profiles for wind turbines. The broad, flat base of curved blades is followed by a curved pattern at the top. In general, they are more suited for producing energy. The curved side of the blade attracts air more quickly than the flat side, increasing the blade's rotational speed. The potential for producing energy is further increased by the fast rotation of curved blades. Out of the three-blade designs, these blades have the highest energy efficiency. Furthermore, these are highly suited for energy production since their curved shape, when combined with an appropriate lift design, helps generate significantly higher torque.

2) Number of blades: Generally speaking, a wind turbine should have between one and five blades. It is not advisable to use a single blade because this can cause tension on the tower and cause stability problems. Using two or three blades can help to lessen this issue. In actuality, a three-blade wind turbine is frequently used since it achieves a balance between producing electricity and efficiency. Three-blade wind turbines often operate well and provide a significant amount of electricity. On the other hand, compared to three-blade turbines, turbines with more blades generate less power and have lower overall efficiency due to increasing wind resistance.

3) Angle of Attack: An essential aerodynamic measure, the angle of attack is the angle created by the direction of the approaching wind and the chord line that joins an airfoil leading and trailing edges. The performance of wind

turbines and other airfoil-based devices is significantly influenced by this angle. In an ideal situation, wind turbine blades would function between an ideal range of angles of attack—roughly 10° and 15° . This range has been carefully chosen after thorough investigation and analysis, taking into consideration a number of variables like the intended power output, wind speed, and blade design. Given this range, two fundamental aerodynamic forces are balanced:

- Lift: As the angle of attack is increased, the turbine blades experience a stronger lift force. More kinetic energy from the wind may be extracted by the blades thanks to this lift force, increasing power production.
- Drag: On the other hand, as the angle of attack goes beyond the ideal range, the drag on the blades also increases. The efficiency of the turbine can be hampered by excessive drag, which can also lead to needless blade wear and tear and worse long-term performance.

4) Angle of Twist: The tilt between a blade's top and lower end-plates is described by a metric called the twist angle. The angle indicates the extent to which the orientation of the blade shifts from top to bottom. Stated differently, it measures the amount of twist the blade experiences along its length. Studies indicate that the ideal pitch angle at 25 mph is 20 degrees.

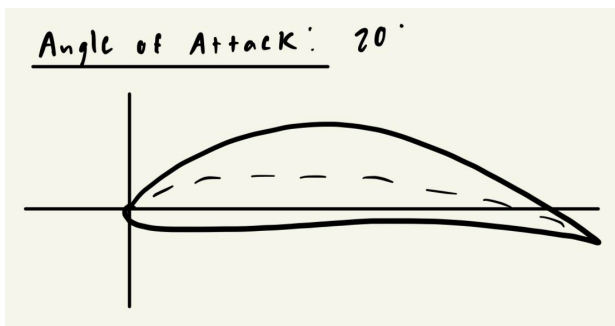


Figure 1.2 Angle of Attack

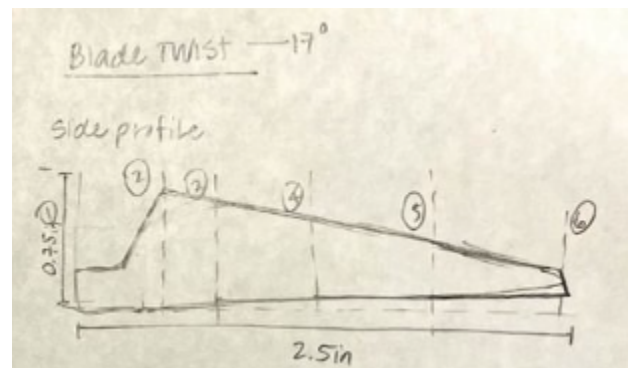


Figure 1.3 Blade Twist

1.2.2 The Tower

A wind turbine tower is a tall structure, usually composed of concrete or steel, that supports the rotor, gearbox, generator, and other related machinery as well as other essential parts of a wind turbine.

Apart from questions surrounding the materials of a wind turbine tower, one must consider:

- 1) Cost: In wind turbine structures, the tower cost usually makes up about 20% of the entire turbine cost. To extend, for example, a fifty-meter tower by ten meters costs an extra fifteen thousand dollars. Therefore, reducing the overall cost of energy generation requires optimizing tower building.
- 2) Structure: Rotor blade stress loads are higher in wind turbines with shorter towers because the blades are subjected to variable wind speeds and bending forces at different angles. Turbine durability is impacted by this variation that takes place between the top and bottom locations of the blades.
- 3) Aerodynamics: Because wind speeds often increase with height above the ground, having a taller tower is helpful in areas with considerable terrain roughness.

Our design aims to address these major objectives; to be structurally sound, yet cost efficient and produce exceptional power output to maximize energy generation.

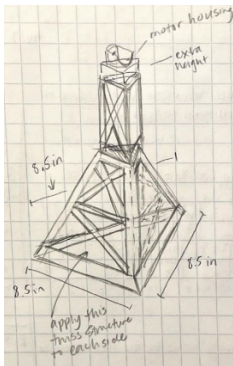


Figure 1.4 Tower Design

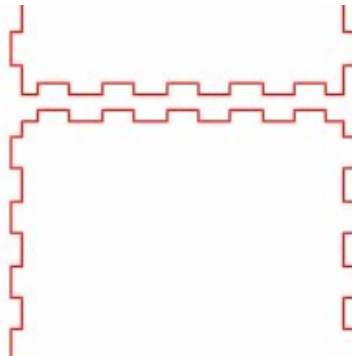


Figure 1.5 Interface Concept

2. Design

The design and analysis of the rotor blade and turbine tower were accomplished using SolidWorks, a software that supplied the 3D computer aided design and analysis software needed for this project. In the design process, we used SolidWorks to procure 3D models of our wind turbine components. Once our models were finalized, we could use SolidWorks Simulation to run finite element analysis on our tower which uses plots for displacement, stress, strain, and factor of safety upon applying some fixtures and external loads. The design details for our rotor blade and turbine tower are as follows:

2.1.1 Rotor Blade

We utilized a three-blade configuration for our horizontal axis wind turbine to control the tradeoff between added weight and power output/efficiency. A turbine with an odd number of blades is subject to stability issues while adding more than three blades yields minimal improvements in efficiency but drives up material and manufacturing costs. The length of each blade is fixed at 2.5 inches. The maximum twist angle of each blade is 13 degrees at the root of the blade and decreases to a minimum of 0 degrees at the tip (Fig. 1c). This yields an angle of attack of 13 degrees for our wind turbine blade. We lofted the cross-sectional shape of each blade around the shape of an airfoil to achieve the lift needed to generate power. Figure 1b displays the shape of the blade from a top-down viewpoint.

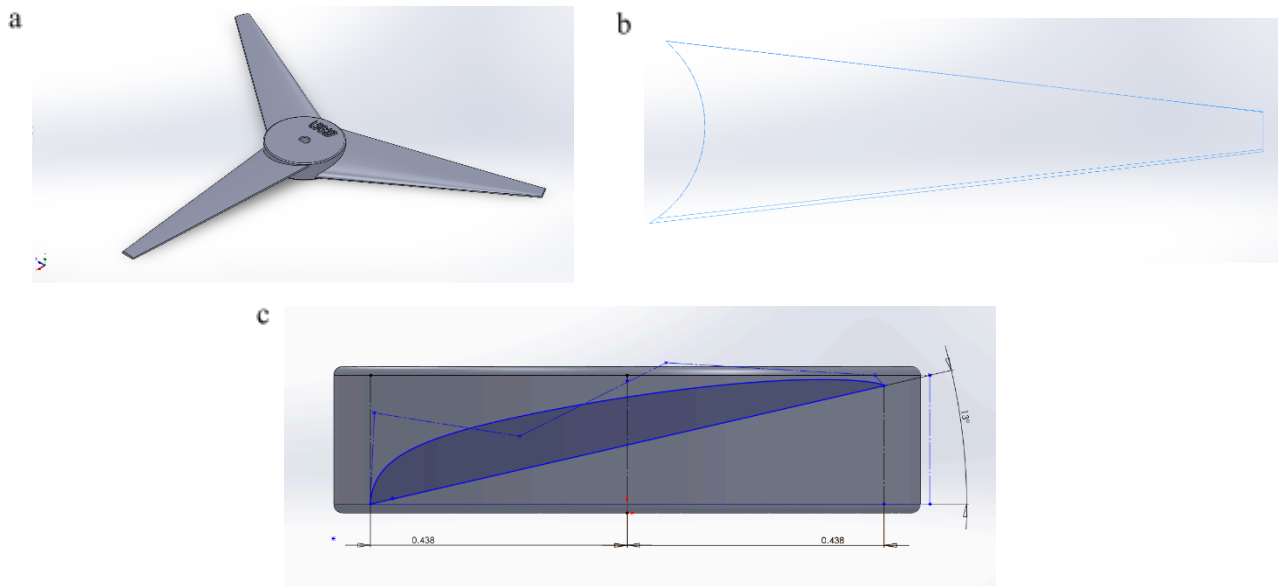


Figure 1 | Wind Turbine Blade Design. a, Isometric view of turbine blade. **b,** Shows an outline of the top-down view shape of the blade. **c,** Shows the cross sectional shape of the blade along with the maximum angle of twist at the root.

2.1.2 Turbine Tower

The schematic of our tower involves a two-piece design. The bottom piece (Fig. 2b) consists of the base and the top piece (Fig. 2a) holds the motor and its housing. Both pieces incorporate a truss structure design for optimized structural integrity and material usage. The two pieces interface via finger joints (Fig. 2c).

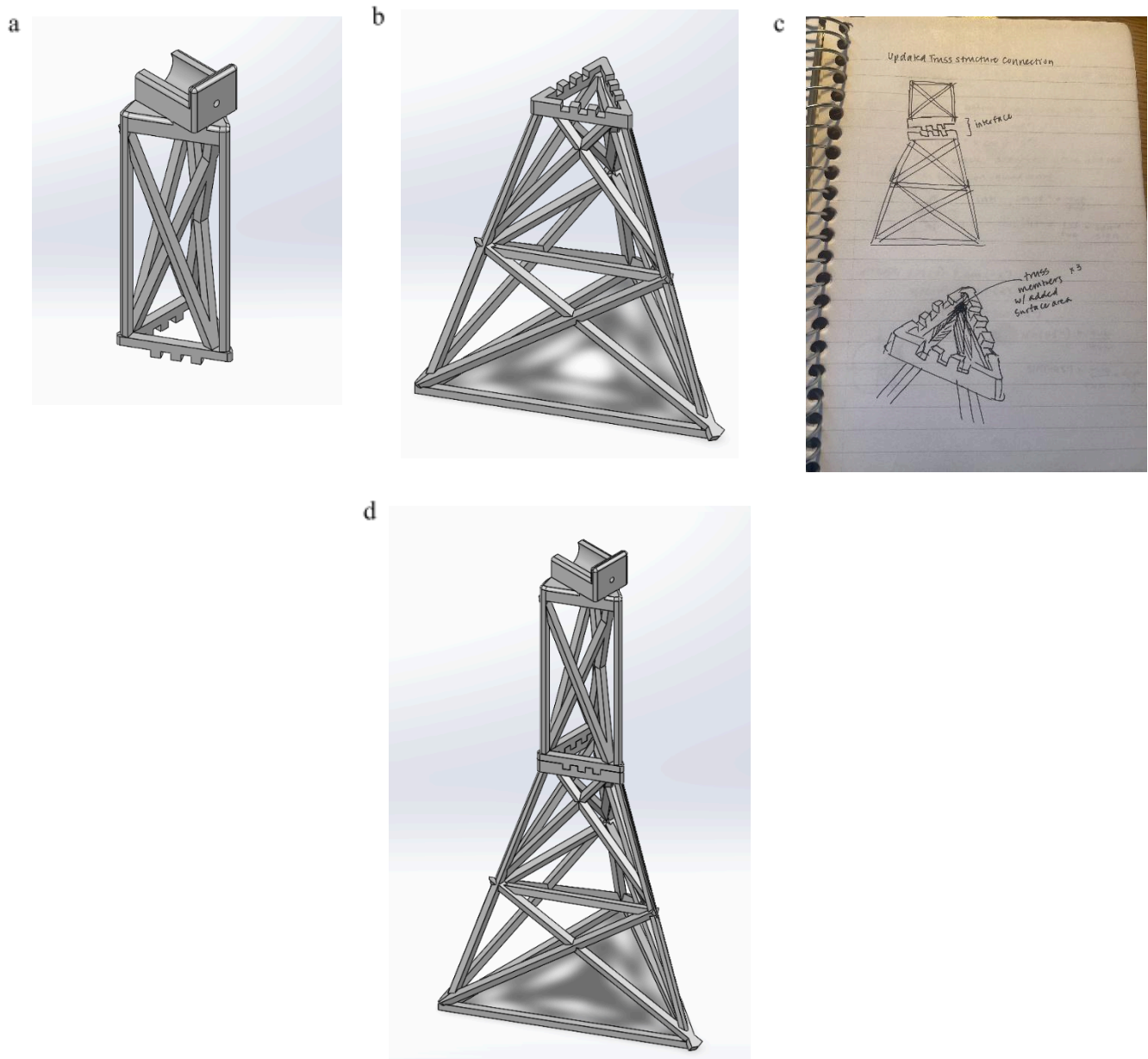


Figure 2 | Turbine Tower Design. a, Isometric view of top turbine piece. b, Isometric view of bottom turbine piece. c, Hand drawing of the interface between the top and bottom pieces showcasing finger joints. d, Isometric view of tower assembly.

2.2 FEA Simulation

Finite element analysis is a computational technique used to predict how structures will respond to various forces, stresses, strains, or other physical effects. This project utilized SolidWorks Simulation as a tool for conducting FEA on our tower assembly. The process for this analysis involved first the creation of a mesh that divided the tower up into many 10-node quadratic elements. Next, boundary conditions were applied. In the case of this project, one fixture condition was applied to the base of the tower and one load condition of 5lbs was applied to the motor housing. Finally, using mathematical methods, the FEA software solves the system of equations derived from the relationships between the elements, material boundary conditions, and material properties. Once the system is solved, SolidWorks Simulation can output graphs of stress, strain, displacement, factor of safety, and more.

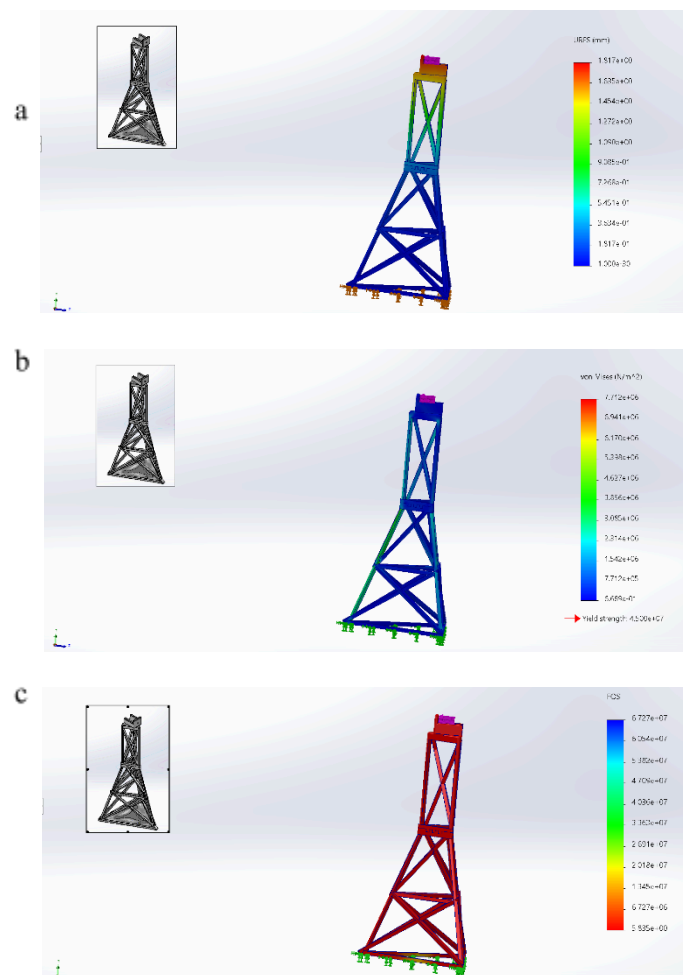


Figure 3 | Tower FEA Results. **a**, Plot showing deflection (displacement) results with a maximum value of 1.817 mm. **b**, Plot showing the von Mises stress results with a maximum value $7.712 \times 10^6 \text{ N/m}^2$. The yield strength of the medium-high impact acrylic is $4.5 \times 10^7 \text{ N/m}^2$. **c**, Factor of safety plot showing a minimum value of 5.8.

The graphs in Figure 3 showcase the results of the study mentioned above. When 5 lbs of force is applied to the motor housing, the maximum displacement seen by the tower occurs at the motor housing and has a value of 1.817 mm (Fig. 3a). Fig. 3b gives the plot of the von Mises stresses on the tower. The maximum stress on the tower is $7.712 \times 10^6 \text{ N/m}^2$, a value below the yield strength of the tower material ($4.5 \times 10^7 \text{ N/m}^2$). This will ensure the tower returns to its original shape after deformation. If the maximum stress were greater than the yield strength, a portion of the tower deformation would remain permanently deformed upon applying the load. Lastly, the factor of safety plot expresses how much stronger this system is than it needs to be for our load. A minimum value of 5.8 indicates our system is 5.8X stronger than it needs to be and therefore will not fail.

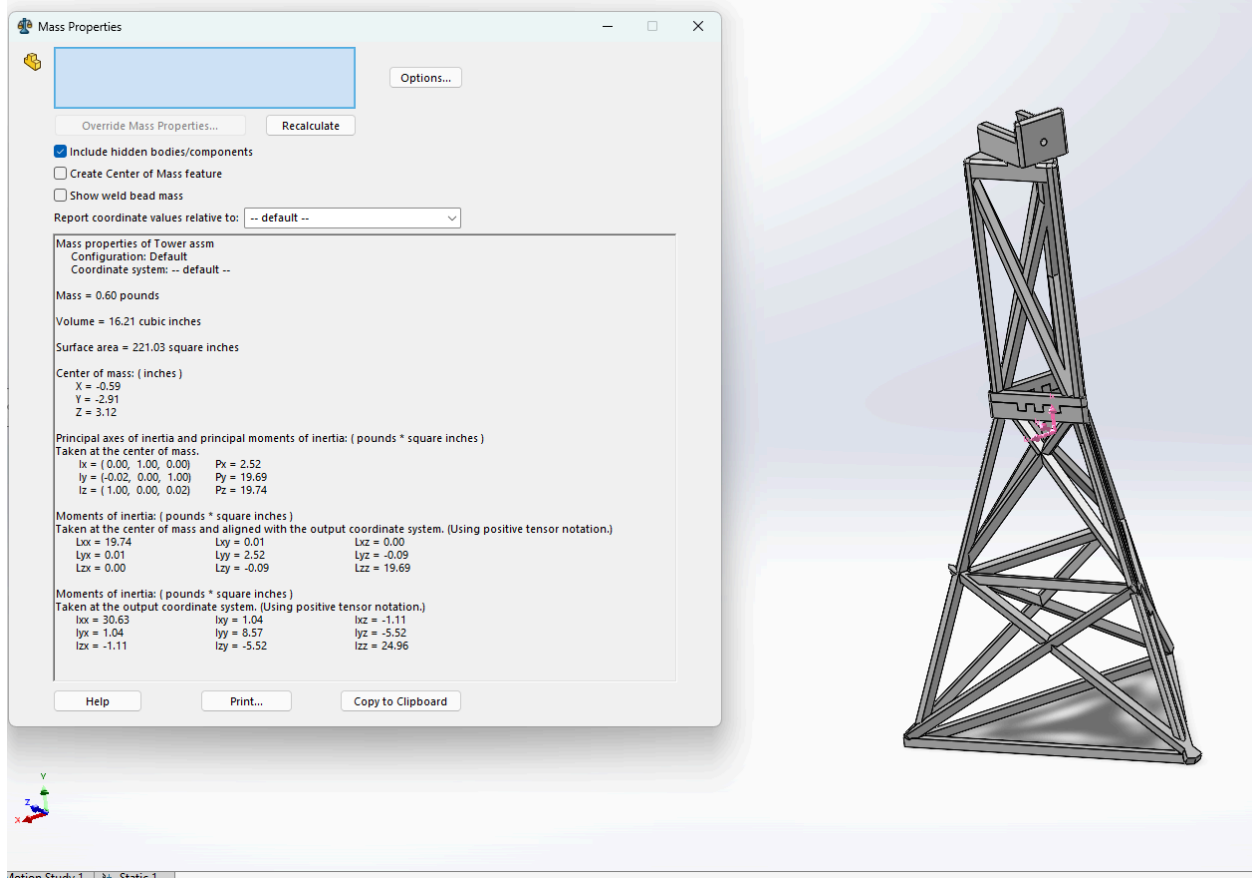


Figure 4 | Mass properties. The volume of the tower is 16.21 cubic inches

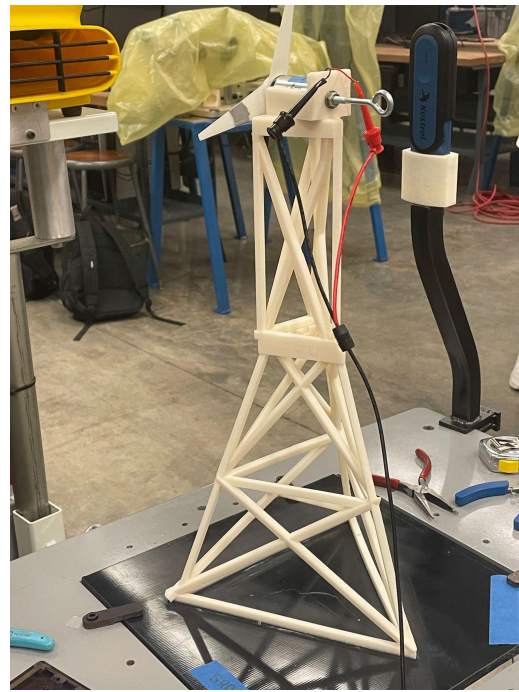
3. Testing Procedure

Below are the steps we took to test our tower for both power output and deflection:

1. Firstly the base of the tower (16" x 16") is secured to the testing table and tightened using tabs on all four sides of the base. The motor is fitted into the chassis with zip ties to ensure that it stays stable during the testing.
2. The motor is hooked up to the potentiometer so that we can measure the Voltage (V), Current (mA), Power (mW) and Resistance (Ohms). Next we made sure to angle the RPM meter towards the taped blade to get readings on how fast the turbine blades spin.
3. Starting with a power output of 475 mW, we took readings of the voltage, resistance, and current. We increased the power drawn from the tower in measurements of 100 mW as closely as possible and noted down our observations.
4. The data was organized into a table and a hard copy of our data was collected from the first portion of our testing.
5. Next, we removed our baseplate from the table and prepared for the deflection testing portion of the test. We weighed our entire structure and subtracted the weight of the baseplate to get just the weight of our tower (233 grams).
6. We secured the tower to the deflection testing table again and centered the gauge towards the middle of our motor chassis. The pulley system was attached to the eye hook on the end of our chassis.
7. We began with attaching a 100g freeweight to the pulley and measured the displacement (mm), slowly increasing the weightage. All the data collected from our tests are compiled below.



Team collected data through reading potentiometer and reading the rpm meter.



The set up of the tower facing the fan on the testing table. Picture shows the attachment method of motor.

3.2 Testing Results

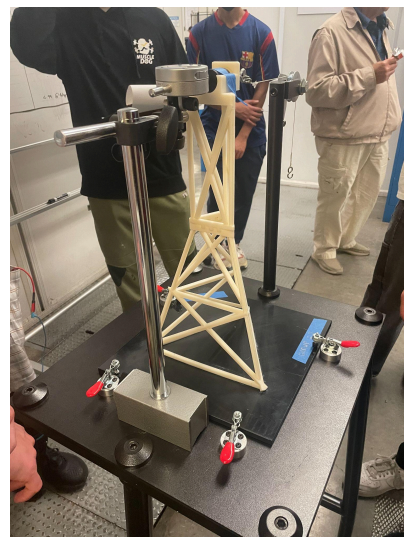
3.2.1 Wind Turbine Power Generation Measurements

Table 1

Voltage (V)	Power (mWatts)	Current (mAmps)	Rotational Speed (rpm)
5.00	475	95	72.21
4.92	560	113.8	70.98
4.75	660	141.1	70.41
4.75	760	165	69.36
4.65	860	186	68.43
4.50	960	215	67.64
4.49	1060	236	67.12
4.26	1160	280	65.31
4.20	1260	300	64.54
3.90	1360	347	61.94
3.90	1460	370	62.19
3.79	1560	400	59.94
3.00	1660	520	50.80



Potentiometer hooked up to apparatus and showing readings



Set up for tower for deflection test, gauge and pulley shown

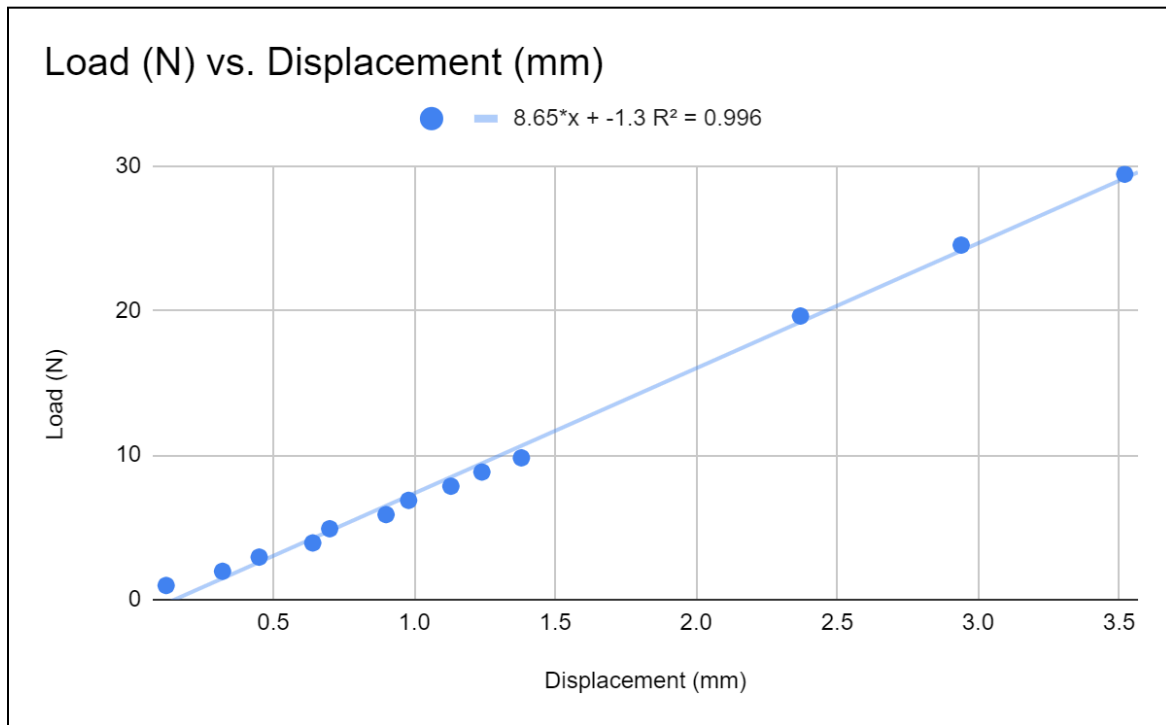
Table 2:

3.2.2 Deflection Measurements

Load (N)	Displacement (mm)
0.981	0.12
1.962	0.32
2.943	0.45
3.924	0.64
4.905	0.7
5.886	0.9
6.867	0.98
7.848	1.13
8.829	1.24
9.81	1.38
19.62	2.37
24.525	2.94
29.43	3.52

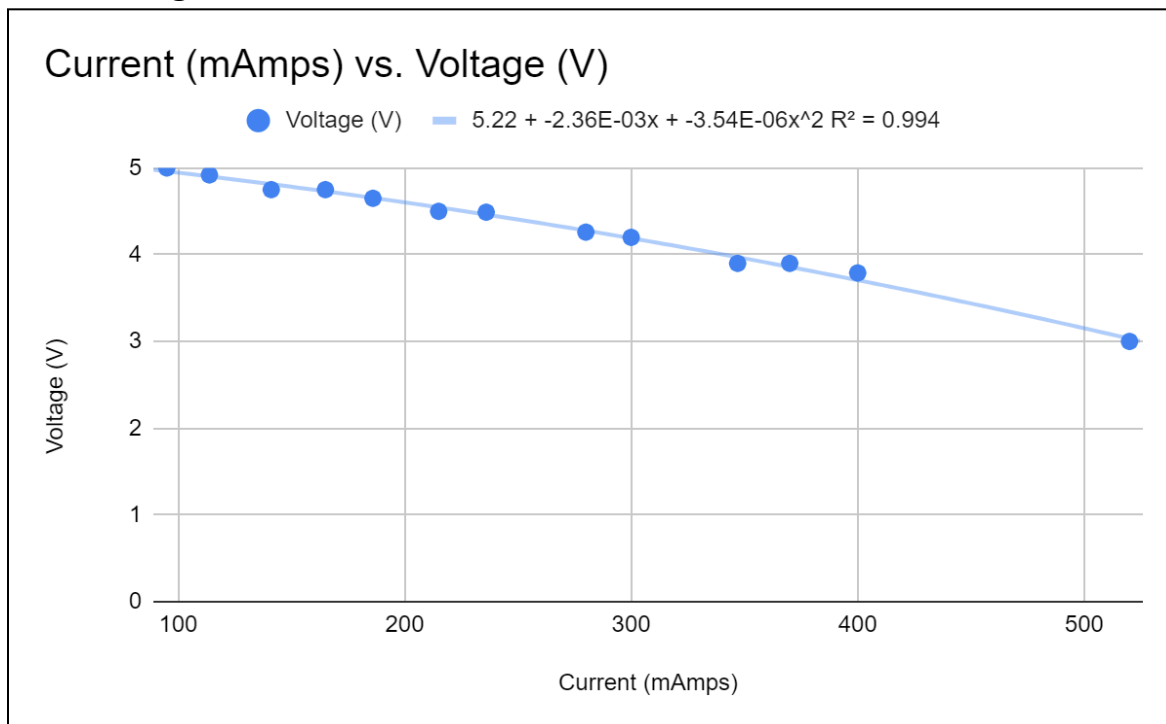
3.2.3 Deflection Test Data Plot

Plots of Deflection Test Data:



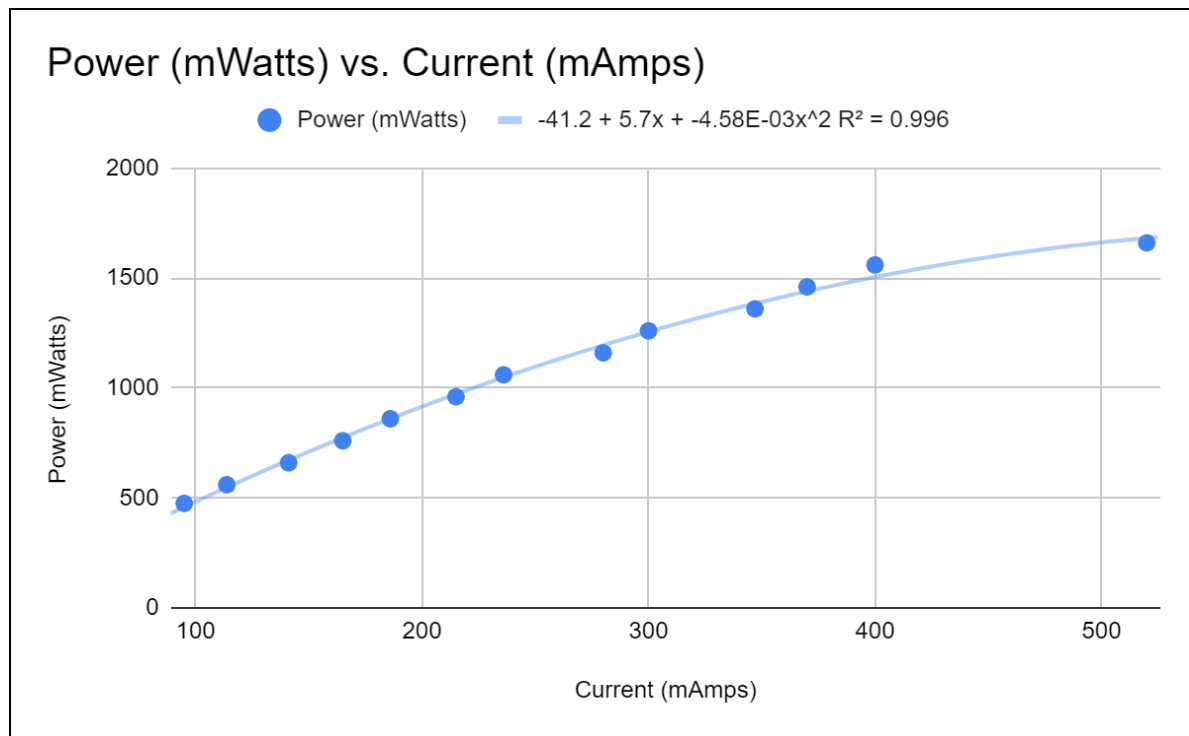
3.2.4 Voltage and Current Plot

Plot of Voltage and Current:



3.2.5 Power Output and Current Plot

Plot of Power Output and Current:



3.2.6 Measure of Efficiency of the Turbine

In order to calculate the efficiency of our turbine we divide the observed power output by the theoretical output.

The formula for the theoretical output of a turbine is given below:

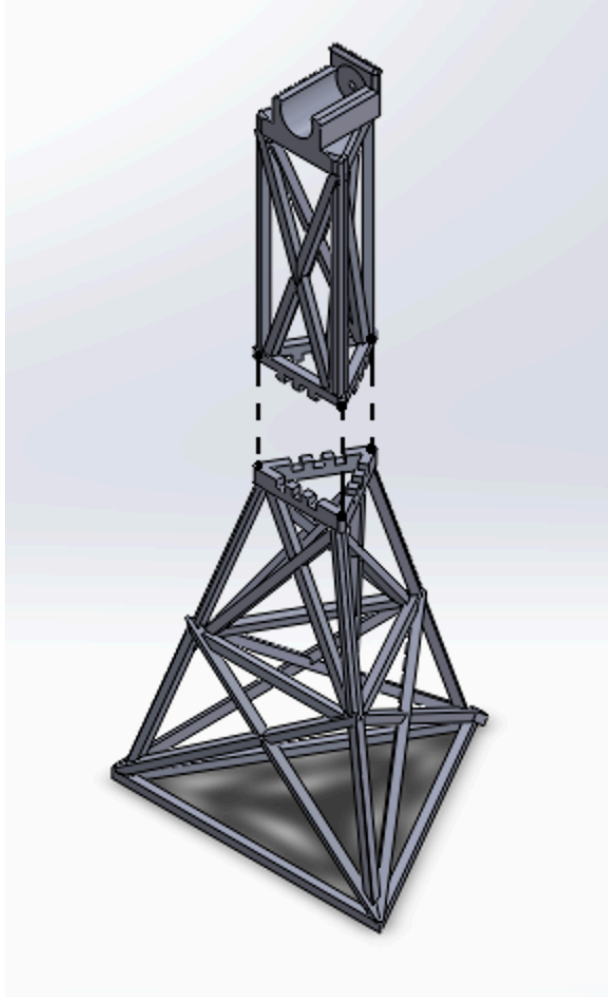
$$P = \frac{1}{2} \rho A v^3 C_p$$

1. ρ is the density of air at around sea level which is 1.2 kg/m^3
2. A is the swept area of the blades which can be calculated by πr^2 where the radius is equal to 2.5 inches. ($A = 0.013 \text{ m}^2$)
3. v is the wind speed in m/s which is 10.774
4. C_p is the theoretical amount of energy that can be collected from the wind according to the Betz Limit which is around 0.4

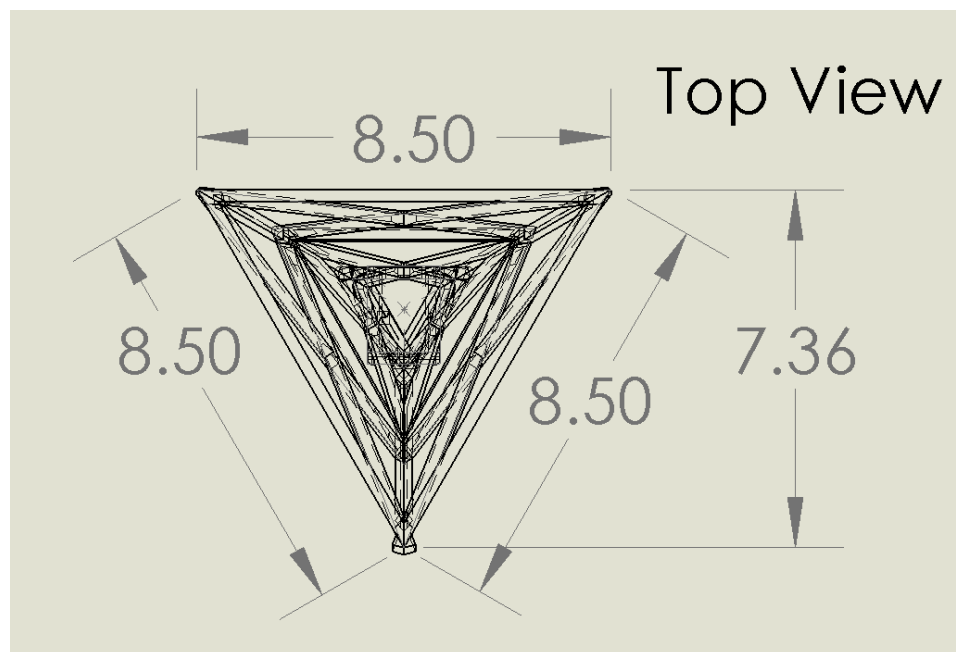
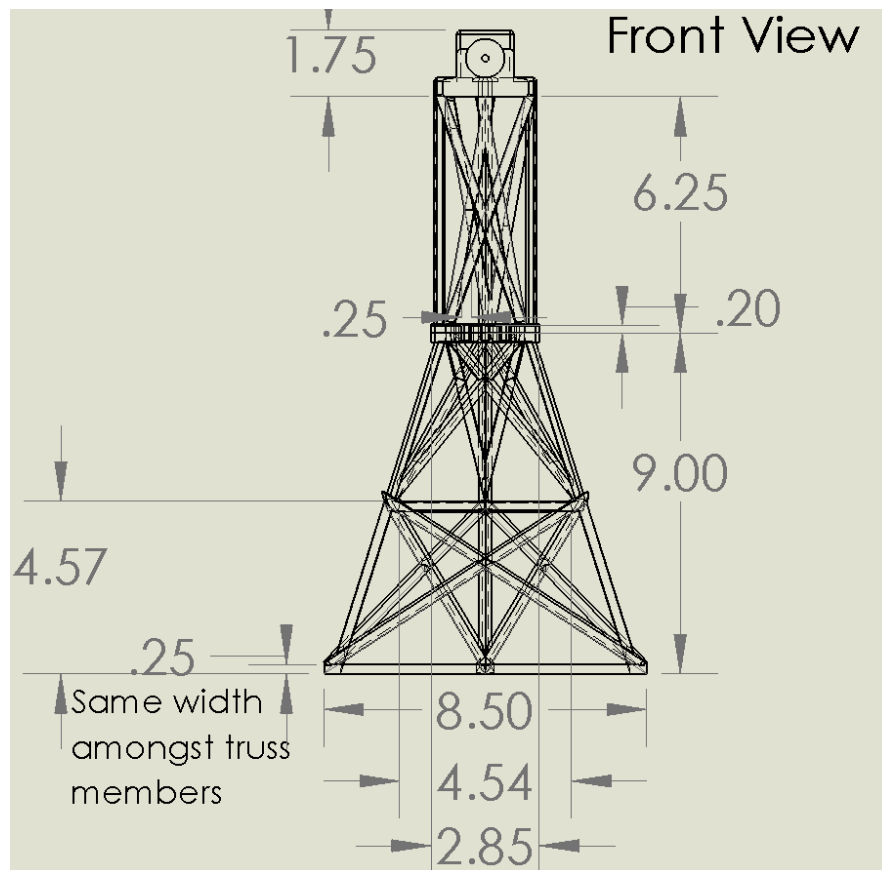
The theoretical power output is then 3.902 Watts. Our Tower was able to achieve a max power output of 1.66 Watts. The calculated efficiency is (experimental/theoretical) 0.43 or **43%**.

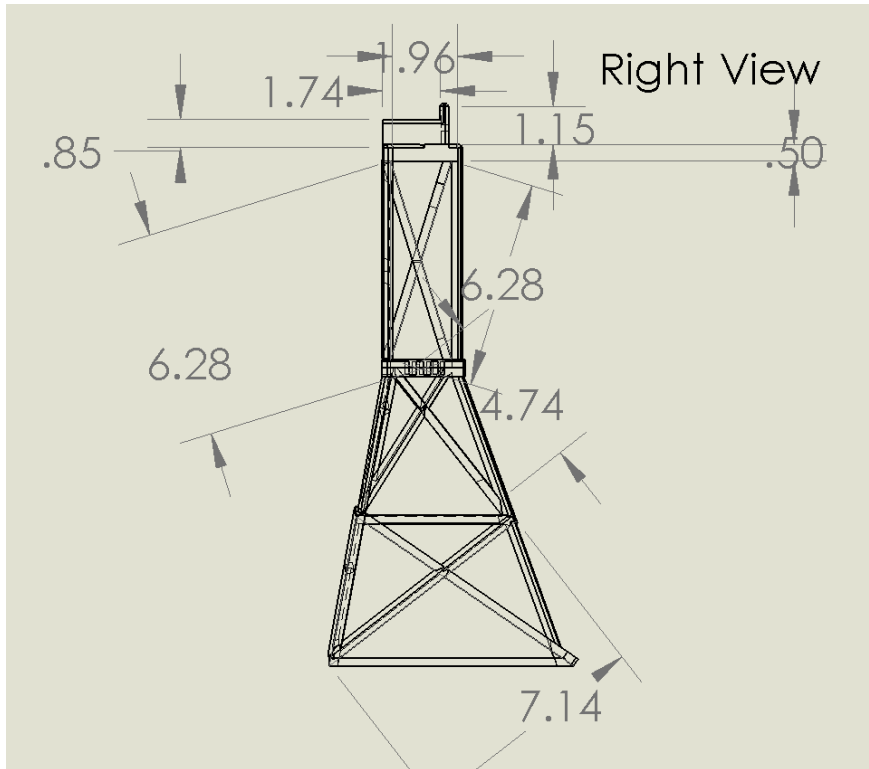
4. CAD Drawings

Exploded View:

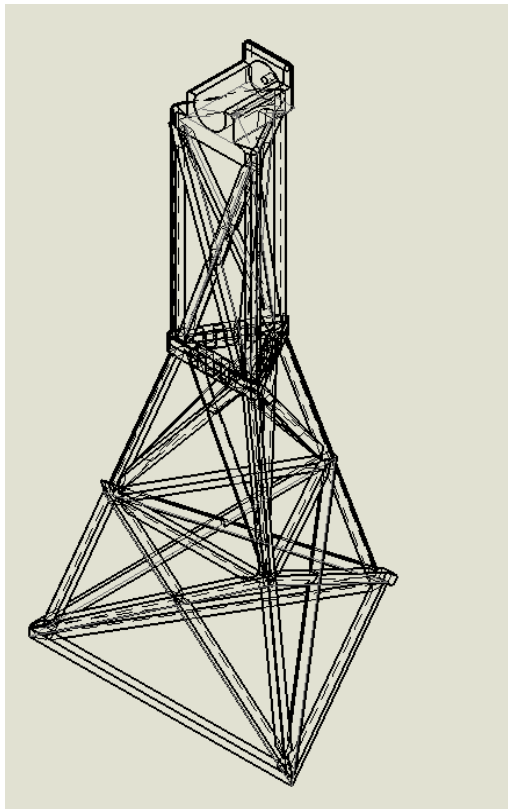


2D Drawings:





Isometric View:



Conclusions

Overall, from this construction project our team learned a lot of valuable information about the design of wind turbines and the general process of developing a project using CAD software. We encountered a few problems during the modeling and printing phase of the project but we were able to innovate and arrive at an effective solution given the time constraints. The results from our testing showed that we had a relatively high power output and that the displacement of the tower was average. We could have made certain improvements to the overall structure of the tower but it is still durable yet lightweight due to the diagonal support rods.

One way we succeeded was using a triangular base structure with hatched supports in between which added extra stability without adding too much material to the print. Additionally the teeth grooves in both the bottom and top parts of the tower proved to be a very secure attachment method. The prominent triangles and symmetry within the design helps keep the tower firm while distributing stress loads evenly throughout.

However, we did encounter some obstacles when printing the assembly files. The top part of the base section had poor connection points between the truss members, causing a severe weak point within the tower. After we came to this realization, our team decided to redesign and reprint the base so that the teethed surface had more interface with the truss rods. This way the tower retained its original shape and height without too much alteration to our initial idea. From this dilemma we were forced to return to the original sketch and determine where we went wrong. Throughout this entire process we acquired valuable skills such as incorporating ideas from each team member, applying practical knowledge from what we learned in lecture, and conducting extensive research on industry standards for turbines.

In conclusion, our team's journey through the wind turbine construction project provided invaluable lessons in informed design, innovation, and effective communication. Despite initial challenges with modeling and printing, we successfully navigated these obstacles through critical thinking and iterative improvements, ultimately creating a durable yet lightweight tower structure. Moving forward we aim to apply our knowledge to continuously improve our manufacturing skills in future engineering projects.

Recommendations for Future Work:

As we look back at our wind turbine project, there are several key areas that need improvement. During the design and printing process of our tower, we encountered several issues during the process. Truss members proved to be difficult to CAD, leading to excess material protruding from the sides of the imperfect truss members. Our top piece had gaps in the truss member connection, which not only affected the visual appearance but also affected the tower's structural stability. Another issue we came across was that our top and bottom interface was slightly misaligned. This may have been due to the fact that our bottom piece had been re-designed and the assembly CAD file was not updated; we should have mated the updated pieces in the SolidWorks assembly to double check if the measurements were correct. For our top and bottom piece connection, our interface teeth were exactly the same size on either side, leading to an interference fit and a lot of sanding. We should have designed one set of teeth to be smaller for an easier fit.

Additionally, we could have considered trying some different blade designs to increase the final power output. Although we initially created a blade with a 13-degree angle of attack and twist angle, we can try other blade shapes and angles to compare power generation. We also could have tried a different tower design to see if it could handle the larger loads during FEA testing. In actual testing, we should try to reduce human errors when adjusting the potentiometer and collect more reasonable and realistic data points, so as to obtain a more reliable and closer data set.

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Appendices

Appendix A - Wind Turbine Power Generation Results

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Wind Turbine Tower stiffness test

Team member names:

Lab section 27 Total weight (grams) 233

Deflection Measurements

Data Points	Load (N)	Displacement (mm)	Observation
1	100 g	.12	
2	200	.32	
3	300	.45	
4	400	.64	
5	500	.7	
6	600	.9	
7	700	.98	
8	800	1.13	
9	900	1.24	
10	1000	1.38	
11	2000	2.37	
12	2500	2.94	
13	3000	3.52	

Appendix B - Tower Stiffness Test

University of California
Mechanical Engineering Department - E26

Wind Turbine Power Generation test

Team member names:

Lab section 27

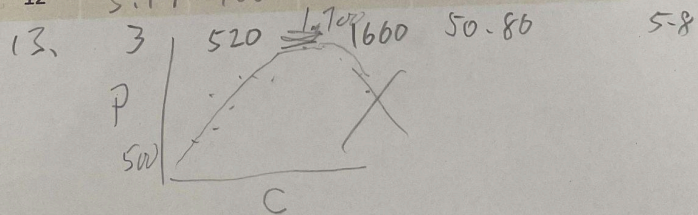
Wind speed (mph) 24.1
Measured at the rotor location

Power Measurements

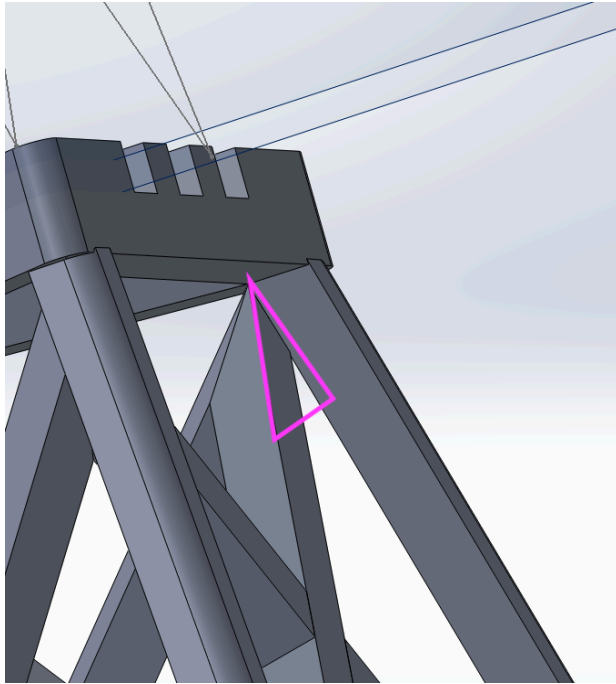
open circuit 5.54

75.47

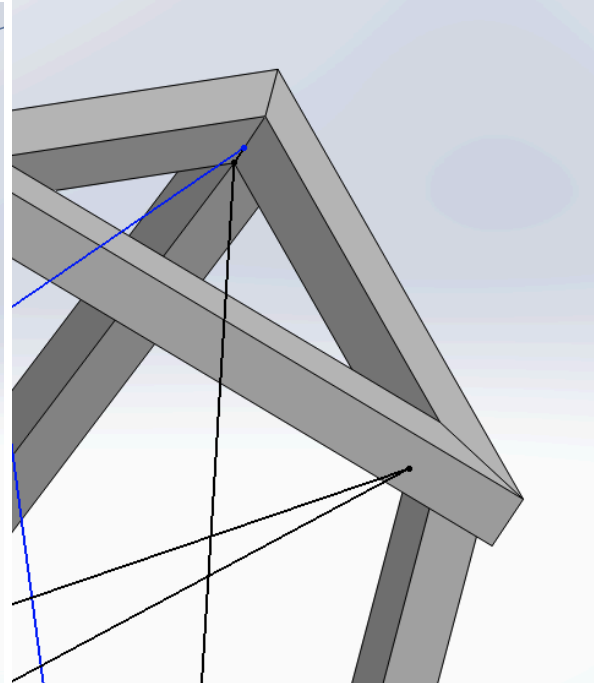
Data Points	Voltage (V)	Current (mAmp)	Power (mWatt)	Blade Rotational Speed (rpm)
1	5.00	95	475	7221
2	4.92	113.8	560	70.98
3	4.75	141.1	660	70.41
4	4.75	165	760	69.36
5	4.65	186	860	68.43
6	4.5	215	960	67.64
7	4.49	236	1060	67.12
8	4.26	280	1160	65.31
9	4.2	300	1260	64.54
10	3.9	347	1360	61.94
11	3.9	370	1460	62.19
12	3.79	400	1560	59.94



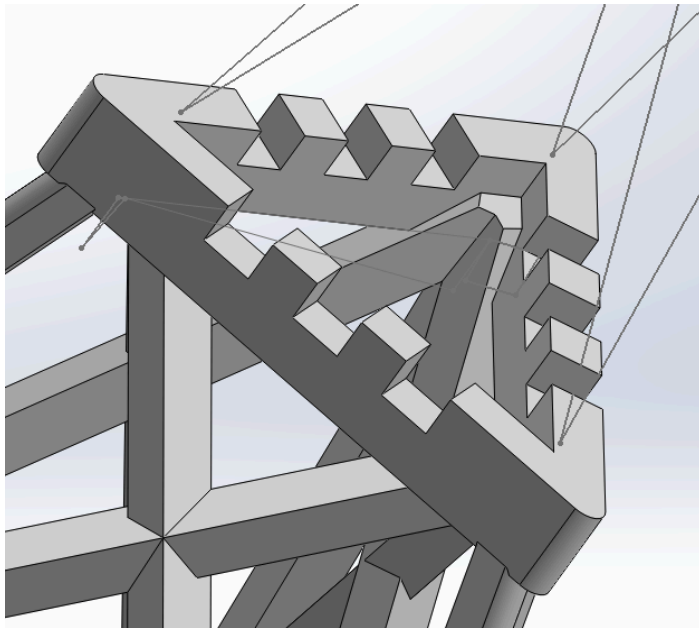
Appendix C - CAD Design Iteration Process



a) only 1 singular plane connecting truss structures leading to print failure; idea to design wedges



b) updated CAD design to instead connect truss members to interface area



c) final updated bottom piece, with added surface area and stronger truss connections