Design and Analysis of a 3D Wind Turbine

Credit: Group 6 with Sahejroop Sethi, Sabeane Escobedo, Dhruv Bisla, Stephanie Schaupp, Nick Atashbar

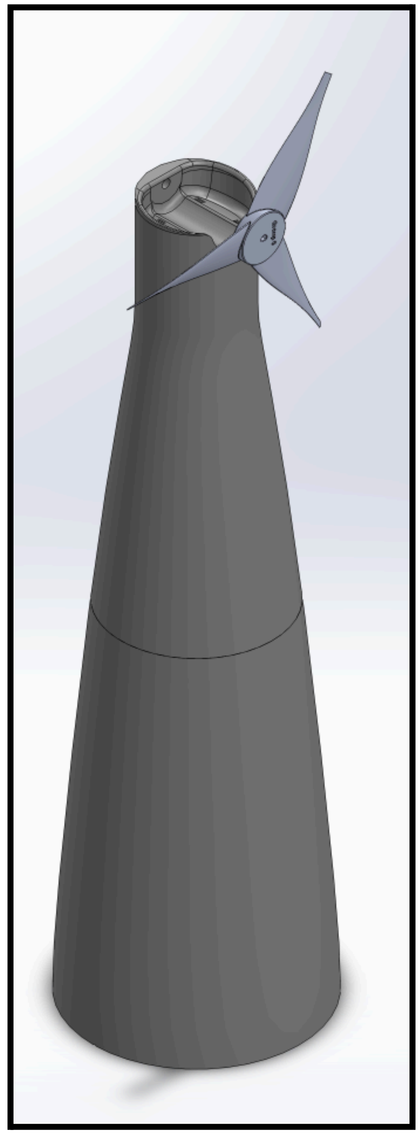

Figure 1a and 1b: Final assembled tower shown in physical form (left) and CAD model (right), highlighting the split design for modular 3D printing and alignment for testing.

University of California, Berkeley
Mechanical Engineering Dept. - E26
Professor Youssefi

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Project Summary

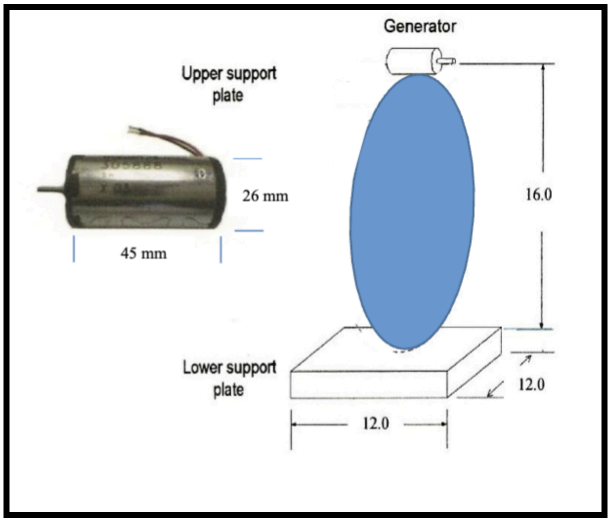

Figure 2: Turbine schematic with base, tower, blade, and motor dimensions

With wind power accounting for nearly 6% of the total electricity generation for the United States, the growing demand for renewable energy has driven the creation and design of thousands of wind turbines. This project aimed to fabricate a small-scale, three-dimensional wind turbine using the CAD platform, SolidWorks, along with its suite of analysis tools. The objective was not only to develop a functional and efficient design, but also to strengthen the team's technical and collaborative skills.

The design process began with researching blade geometries optimized for winds of 25 miles per hour. Since horizontal axis wind turbines have a higher energy output and offer better performance, the team chose a design of that style. Key design parameters included blade profile, angle of attack, and blade number. Several airfoils were considered and reviewed, but the one with the best lift-to-drag ratio in the given wind conditions was selected. Aerodynamic performance was heavily emphasized in the blade design, while structural stability guided the tower design.

Once the wind turbine had been designed, the team conducted finite element analysis (FEA) to assess stress distribution and tower stiffness. Potential weak points were identified and refined before 3D printing the pieces and gluing them together. In addition to virtual tests of the design, two important simulations were conducted to provide further analysis of the wind turbine's overall performance. The team concluded that the tower deflected 0.52 mm, with a stiffness of 17.7 N/mm, and the weight was 1193.4 grams (which includes the 895-gram mounted board; therefore, the wind turbine itself weighed approximately 298.4 grams), and the maximum power generated was 260.99 milliwatts.

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Introduction

Utilizing energy from the wind is one of the oldest forms of mechanical power generation, dating back to ancient windmills and sailing vessels. Today, wind energy plays a pivotal role in global efforts to decarbonize the overall power sector. Wind turbines transform the kinetic energy of moving air into usable electrical energy through a highly coordinated system of aerodynamic and mechanical components. Wind energy systems provide a clean alternative to traditional power generation methods, helping to cut down on carbon emissions and reduce the reliance on non-renewable resources ("Advantages and challenges of wind energy," n.d.). As the global need for low-emission technologies increases, advancements in wind turbine design have become a significant area of engineering development and research.

Modern wind turbines operate by using several blades, shaped similarly to aircraft wings, to capture wind energy and induce rotational motion. As wind moves over the airfoil-shaped blades, a pressure difference generates lift, similar to how lift is generated on an aircraft wing, causing the rotor to spin ("How Do Wind Turbines Work?," n.d.). The rotating blades power a central shaft, which commonly transmits motion through a gearbox, increasing rotational speed before reaching the generator. This mechanical input is converted into electrical energy by the generator's electromagnetic induction mechanism. This electricity is then stepped to the appropriate voltage and transmitted through power lines to supply homes, businesses, and other infrastructure. To improve efficiency, many large wind turbines are equipped with systems that automatically adjust the electrical loading conditions and the angle of the blades as wind conditions change. They also have mechanisms that rotate the entire top section of the turbine to face the wind, helping the system capture as much energy as possible.

This project was conducted as part of a semester-long engineering design course focused on introducing key concepts in mechanical design, prototyping, and performance testing. The overall objective was to design and fabricate a small-scale wind turbine capable of efficiently converting wind energy into electrical power. The course emphasized a multidisciplinary approach, requiring the integration of CAD modeling, aerodynamics analysis, material constraints, and energy conversion principles. The design process involved iterative development of both the turbine blades and support structure, guided by theoretical calculations and validated through physical testing. Groups were tasked with meeting specific performance targets while adhering to strict fabrication and dimensional constraints, fostering practical experience in both analytical engineering and hands-on manufacturing.

The goal of the project was not only to build a functional turbine but also to explore performance trade-offs between power output, structural stiffness, material usage, and manufacturability (in this case, 3D printing). Each group was responsible for producing a blade design that maximized power generation at a wind speed of approximately 25 mph and a tower design capable of minimizing lateral movement (deflection) under load up to 1kg. To achieve this, teams used a combination of CAD, finite element analysis (FEA), and 3D printing.
The constraints required the entire structure to be fabricated from PLA or ABS material and assembled on a 12 x 12 inch base plate. The turbine's tower had to raise the motor shaft exactly 16 inches above the platform, and the tower volume was not to exceed 17 cubic inches. The rotor's swept diameter could not exceed 6 inches, limiting each blade to a maximum length of 3 inches from the center of the hub. In addition, the tower design had to be radially symmetrical with at least three contact points and fabricated in at least two parts to fit within the 3D printer's 9 x 9 x 9 inch build volume.

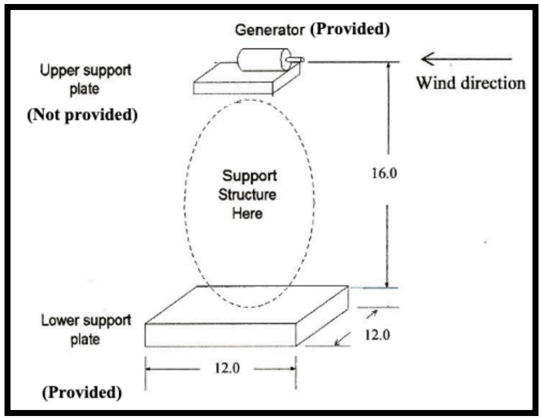


Figure 3: Schematic of the wind turbine assembly showing key dimensional constraints. The tower raises the generator 16 inches above the 12x12 inch base while maintaining structural stability under load and within fabrication limits.

In order to evaluate the wind turbine, both tower and blade performance, two primary evaluations were performed: power output and tower stiffness, both of which are pictured below. To measure power, the turbine was exposed to wind from a controlled blower at approximately 25 mph. A motor, acting as a generator, was connected to a power meter and a variable electrical load. By adjusting the resistance, the current, voltage, and power output were recorded across a range of load conditions to identify the point of maximum power generation. To assess tower stiffness, weights were gradually applied to the tower using a pulley system, while a dial indicator measured the resulting deflection. A plot of load versus deflection was used to determine the structural stiffness of the tower.

	
Figure 4a: Power output test setup (left) showing the wind turbine exposed to a controlled blower and connected to a power meter.	*Figure 4b*: Stiffness test setup (right) showing deflection measurement using a dial indicator as weights are applied to the tower.

Project/Design Overview

The design process for both the blades and the tower was highly iterative, involving several preliminary models that were refined based on printability, performance, and compliance with the constraints. We developed, assessed, and revised multiple concepts throughout the design cycle.

Beginning with the blade design, we started by developing concepts and referencing past work on blade profiles for similarly sized wind turbines. In creating our own wind turbine blades, our primary design freedom is in the shape, or the airfoil of each blade, which contributes to both the lift and drag generated. In optimizing for the power generated, we were able to adjust parameters in addition to the blade profile including the number of blades, angle of twist, and angle of attack. Below are a few sketches of airfoils during our process of evaluating blade profiles.

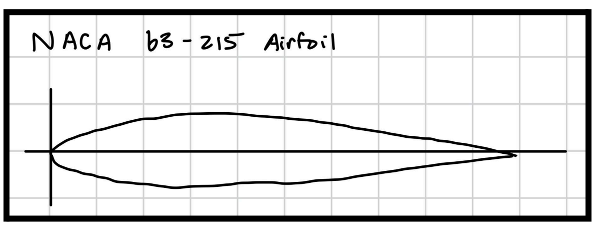
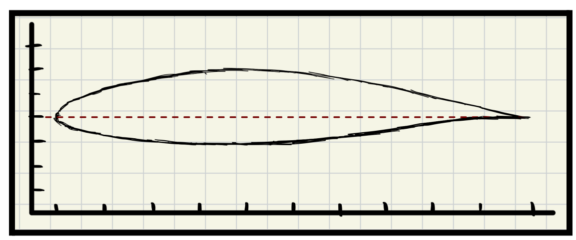
	

Figure 5a: Sketches of evaluated airfoil profiles during blade design, illustrating variations in shape used to analyze aerodynamic performance.	*Figure 5b*: Similar to *Figure 5a*, initial sketch of an airfoil profile.

Moving into Solidworks CAD, we transferred these blade profiles and evaluated the resulting blades. These initial designs are shown below and were modified in subsequent versions to increase angle of attack and blade thickness, improving overall durability and manufacturability.

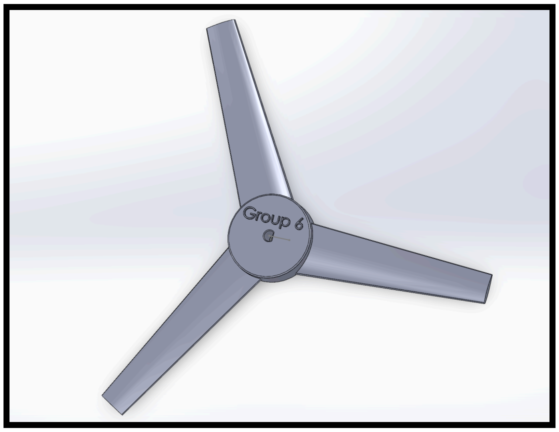
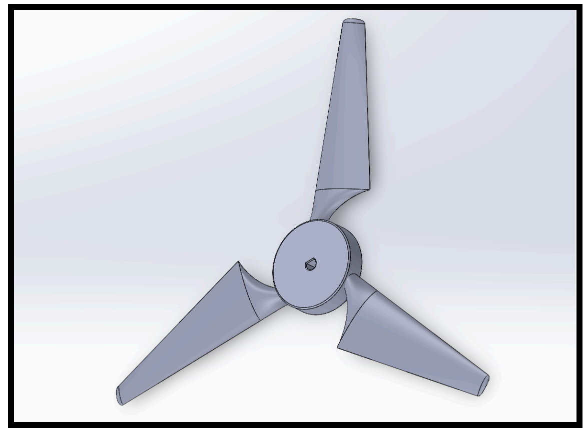
	

Figure 6a: CAD models of initial blade designs; shows a 3D blade design with a relatively low twist and wide chord length.	*Figure 6b:* Features an initial blade concept with an increased blade twist, intended to improve aerodynamic performance at lower wind speeds.

After refining our blade concepts, we shifted focus to the tower, which presented its own unique challenges under the project's structural and material constraints. The goal of the tower was to maximize stiffness given a limited volume of material (17 cubic inches). The fixed design constraints we were given include radial symmetry, a minimum of 3 contact points with the ground, the height of the tower from base to the center of the motor's shaft, 16 inches, the material (PLA or ABS) and, in turn, the Young's modulus of the material. Due to manufacturing constraints imposed by 3d printers, the turbine structure had to be made in two parts, as the height of any piece is limited by a desktop 3d printer's maximum z height. In order to perform the stiffness component of the test, the tower must also include a 3/16 diameter hole for an eyebolt to be attached. To design a tower around these constraints, we first came up with several concepts.

Initial tower concepts relied heavily on open-frame structures (designs that made use of negative space) to achieve stiffness while conserving material (Figures 2-4). While these initial concepts prioritized material efficiency, further evaluation revealed several limitations in their structural performance and printability. The following section details our iterative design process, including the alternatives we explored and the reasoning behind our final tower selection.

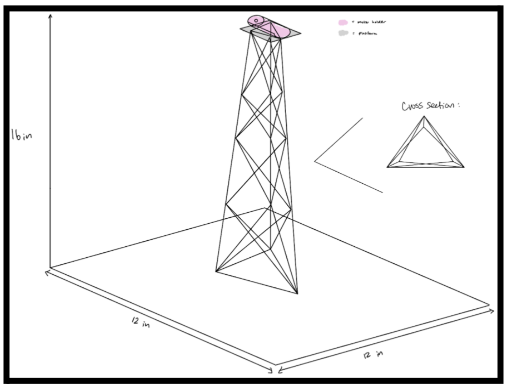
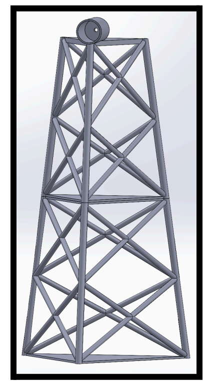
	

Figure 7a: Initial tower concept; shows a freehand sketch of a triangular cross-section open-frame tower design intended to maximize stiffness while minimizing material use.	*Figure 7b:* shows corresponding CAD model of the same concept from *Figure 2a*.

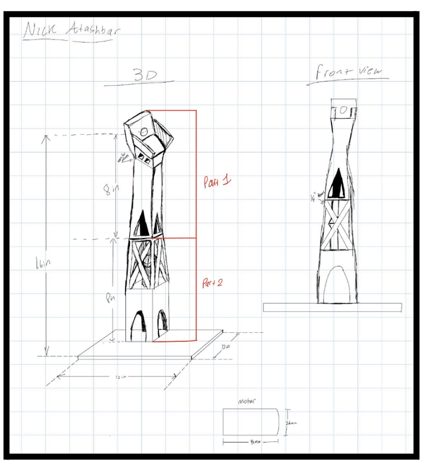
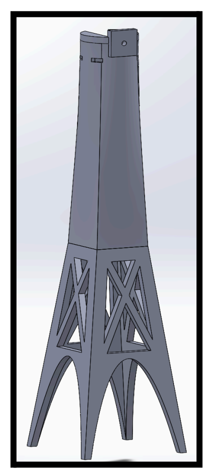
	

Figure 8a: Alternative tower design concept; presents a detailed sketch of a two-part modular design intended to meet the printer height constraint while maintaining structural integrity.	*Figure 8b:* Shows the corresponding CAD model for *Figure 4a.*

Design

Blades

Under the constraints of maximum 3 inch blade radius and 25 mph winds, so the air flowing over the blades is thick compared to the chord of the blade. This means the Reynolds number is only 80-140k. From our concept phase, we had a few options, NACA 63-215, 4412, 63-415, 65-415, and SG 6043. Doing further research on the characteristics and performance of these blades showed that at the speeds relevant to our testing, 63-215 stalls as soon as the flow becomes slightly unsteady while 63-415 has a drop in lift right where we would like to set the blade angle (Shin & Kim, 2020). 65-415 adds significant material which should enhance strength, but likely isn't necessary weight for the blades. Finally, comparing both the 4412 and SG 6043 profiles showed that it has the highest lift to drag ratio in this Reynolds range and preserves smooth airflow up to around 13 degrees angle of attack (Sessarego & Wood, 2015).

With the airfoil chosen, based on the discussion during lecture, we decided to have three blades because of the inflection point which makes it so that any greater and there diminishing returns. Further research also showed that 3 blades offer the most stability, which is desirable considering the high speeds we expect the blades to spin at (Adeyeye et al., 2021).

Referencing Sessarego and Wood's work on optimizing blade twist as a function of r/R, we settled on a total twist angle of 34 degrees.

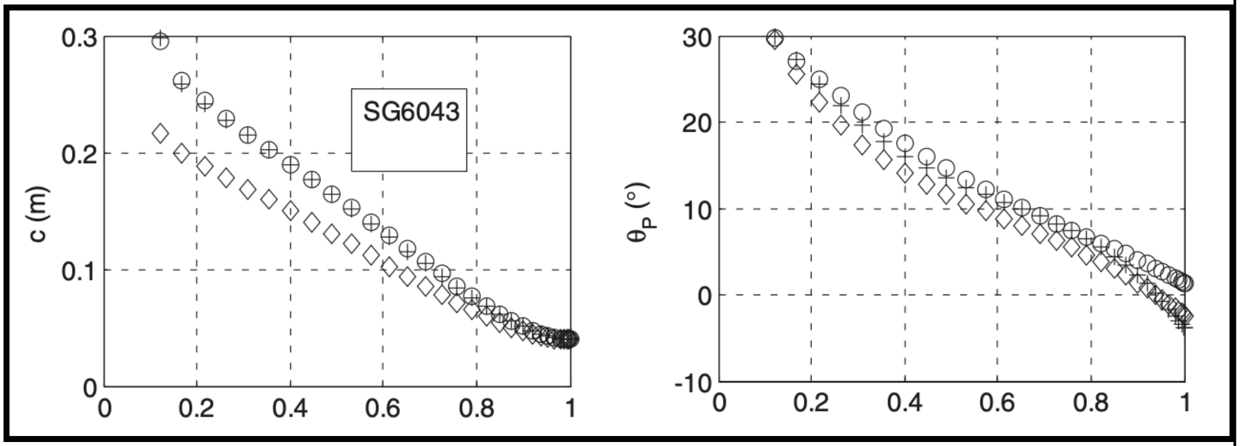


Figure 9: Optimization of chord and twist over r/R by Sessarego and Wood.

Finally, for the angle of attack, literature shows that for such small scale wind turbines like the one in our project, the Reynolds numbers are significantly lower than in typical application of the SG 6043 airfoil at slightly larger scales. The analysis done by the authors in a paper specifically looking at small wind turbines concluded that an appropriate optimal lift to drag ratio is achieved by an angle of attack of about 9 degrees, following a general trend of increasing single digit numbers as the Reynolds number decreases (Chaudhary et al., n.d.). Another paper which experimentally varied pitch angle of the blade arrived at a similar conclusion that 10 degrees was optimal over the range they tested, though this was for even lower Reynolds numbers than what we should anticipate (Wibowo, 2019).

With these parameters chosen for the blade, we moved to Solidworks to model the blade profile. The first step here was to add reference geometry to ensure the parametric design did not exceed the radius and thickness constraints. Then, as is shown in the screenshot below, we added the spline shape of the airfoils with the correct angle of attack, first at the root, then on offset planes towards the outer edge of the blade, appropriately rotating and scaling the profile.

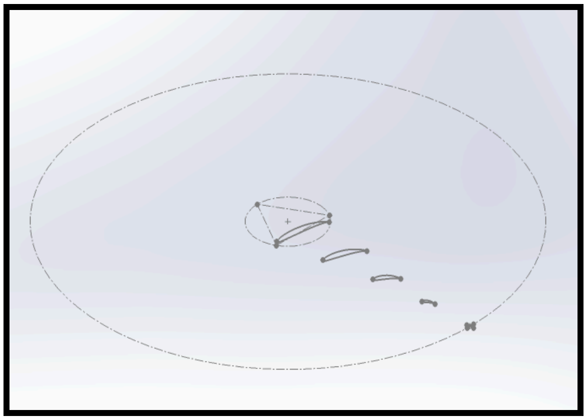


Figure 10a: Solidworks sketch setup of airfoil prior to lofting.

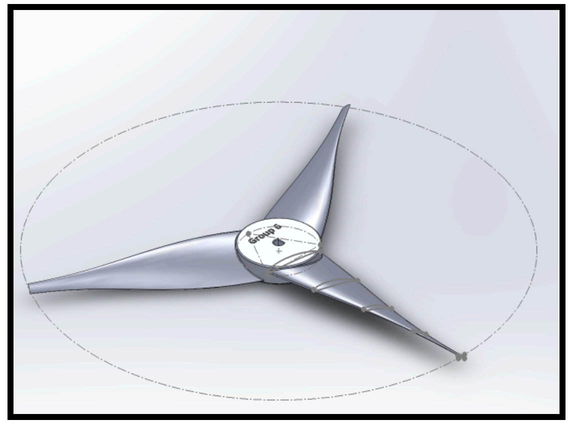


Figure 10b: Completed blade after loft and circular pattern.

Once the profile was lofted from root to the tip, we applied a circular pattern to get the 3 total blades.

Tower

The tower concepts shown in the previous section seem to form an effective structure for the tower in terms of forming a sort of lattice structure to efficiently use material, but we decided to go with the concept that used beam bending principles to design an optimized structure for the loading conditions we expect during the stiffness test.

To meet the radial symmetry criteria, we decided to go with a circular cross section. But because the material farthest from the neutral axis is most important in bending, instead of a solid circular cross section, we decided to use a cross section consisting of an annular ring, such that the tower is hollow in the middle. But because the amount of material needed to maintain stiffness decreases as you move away from the base of the tower, our goal was to find a profile for the cross-sectional variation such that it efficiently places material where it is needed most.

To do this, we wrote a Python program that performed numerical optimization of the tower shape while respecting the volume, height, and maximum radius constraints. Using

Euler-Bernoulli beam theory, $w(L) = \int_0^L \frac{M(x)(L-x)}{EI(x)} dx$, where $M(x) = P(L - x)$, so the goal is to choose I(x) to be as large as possible near the high moment regions (near the base) while meeting the volume constraint. In order to do this, the code discretizes the beam into segments and then approximates the volume and deflection integrals using the midpoint rule. By defining an objective function for the deflection and appropriate constraints, we can optimize for the profile of the radius and thickness over the height of the tower by seeking to minimize the objective. We found that an additional smoothness penalty was needed in the objective function in order to make these profiles smooth functions. Below is the result of the optimization showing the profile of outer radius and thickness of the tower as a function of height, as well as a visual of what this looks like.

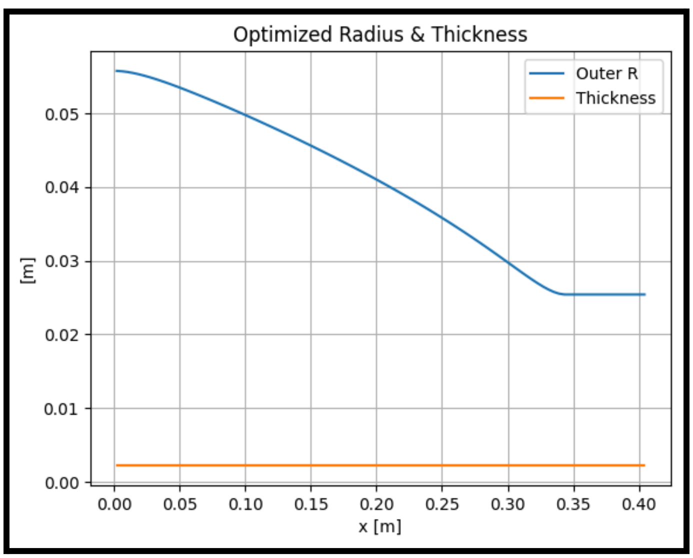


Figure 11a: Result of optimization showing the profile of outer radius and thickness of tower as a function of height

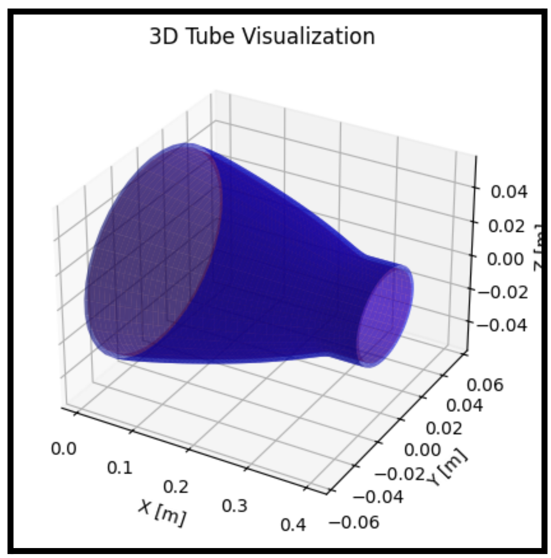


Figure 11b: Visualization of *fig 6a*

Given these results, we wrote some code to use the outer radius and thickness profiles to export the outer and and inner radius profiles as splines in DXF format. This let us then import the DXF files into Solidworks to revolve and then add the motor housing and eye bolt mounting features.

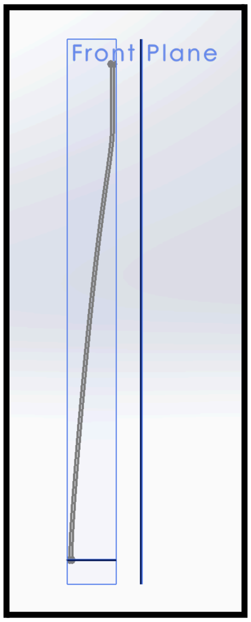
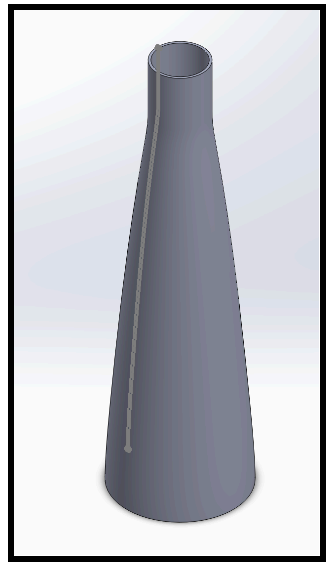
	

Figure 12: Front plane view of tower	*Figure 13:* Complete isometric view of tower

Then, in order to ensure that the motor mounting features would not be a source of a lack of stiffness, we modeled large radii features that connected the motor region to the optimized tower shape. Below is a cross section of what this looks like.

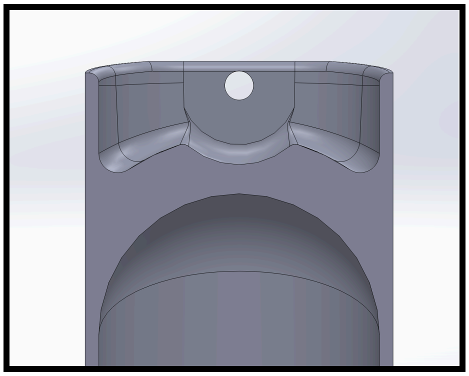
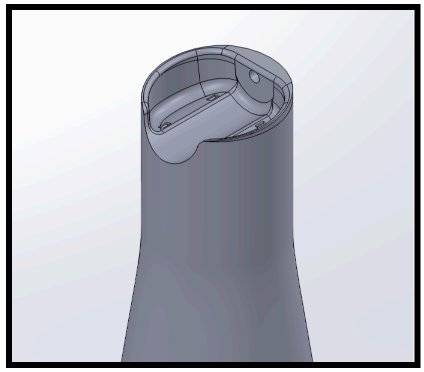
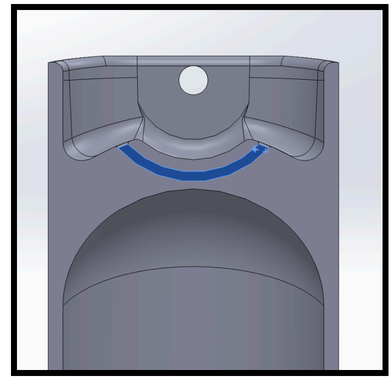
		

Figure 14a: Inside view of motor region	*Figure 14b:* Exterior view of motor region	*Figure 14c:* Ziptie channel features

Since we needed some features to retain zip ties for mounting the motor, the thick curved ribs connecting the motor mount to the tower allowed adding ziptie channel features which integrated well with the rest of the tower *(fig 8c)*.

Finally, we split the tower in half using Solidworks' Split feature, and then modeling what is called a Spigot Lap Joint in order to allow one half to be located onto the other and provide a good surface area for bonding (which is necessary in order to prevent a loss of stiffness from the tower halves joint). This technique is often used in hobby rocketry in combination with shear pins to offer good bending strength, so given the similar loading case, we decided to use it in our design as well.

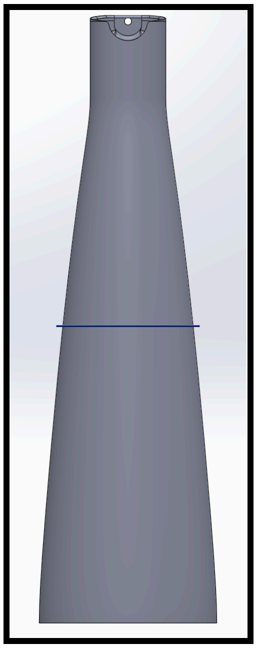
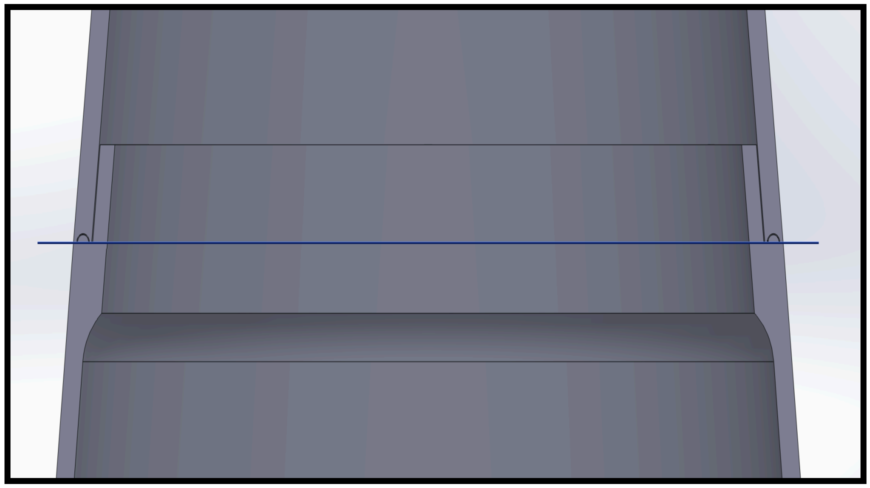
	

Figure 15a: Exterior view of split line	*Figure 15b:* Interior view of split line

Once we completed the design of the tower, we evaluated its stiffness performance using an FEA simulation in Solidworks.

We started by assigning the material of our tower, PLA, and populating the material properties for a custom material in Solidworks, as it does not have PLA in its default material library.

Property	Value
Elastic Modulus	2346500000 N/m^2
Poisson's Ratio	0.36
Shear Modulus	1287000000 N/m^2
Mass Density	1240 kg/m^3
Tensile Strength	45600000 N/m^2
Compressive Strength	60000000 N/m^2
Yield Strength	$6.8*10^{-5}$ K^{-1}

Next, we fixed the bottom half of the tower and then added a rigid connection between the two halves. This is an assumption we had to make in order to complete the analysis as in reality, the glue used to bond the two halves will likely not be perfectly stiff. However, since we are assuming it is much more stiff than the tower, we are letting the connection be simulated as a perfect rigid one. To create our mesh, we used the default mesh density as a starting point for the simulation, as shown below, and this turned out to give good results without meshing failure or infeasible outcome. Finally, we applied the load, which we set to be a force equal to 9.8 N (the force for a hanging 1kg mass, following the testing procedure outlined in the next section). The load was applied on the face of the eye bolt's connection to the tower, and in the direction transverse to the tower.

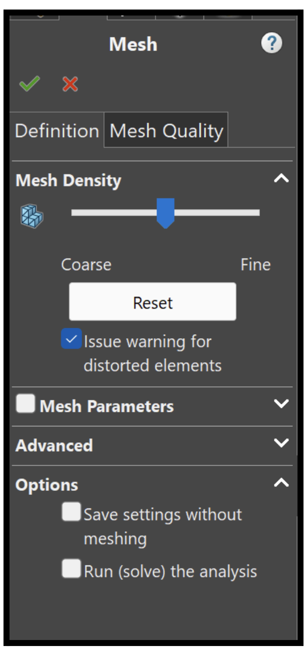


Figure 16a: Mesh feature

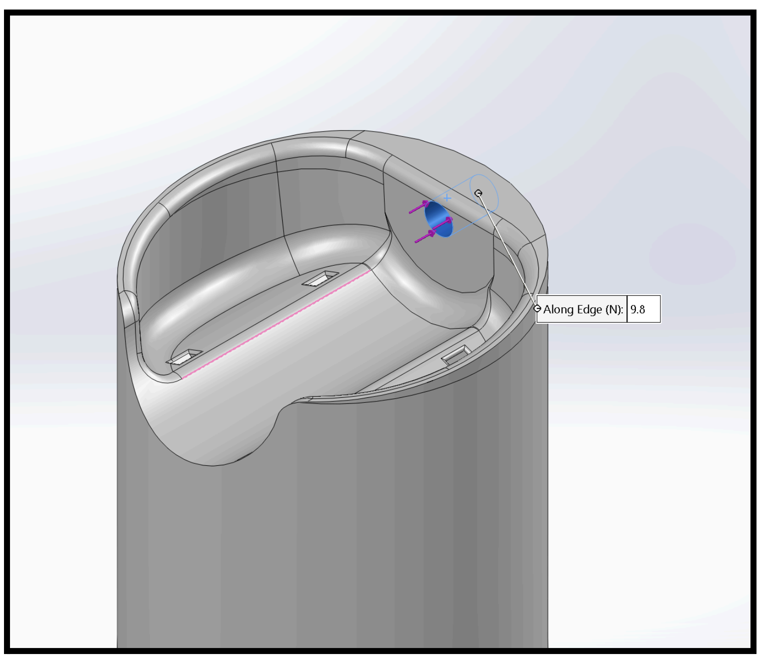


Figure 16b: Applied load of 9.8 N to the eye bolt;s connection to the tower

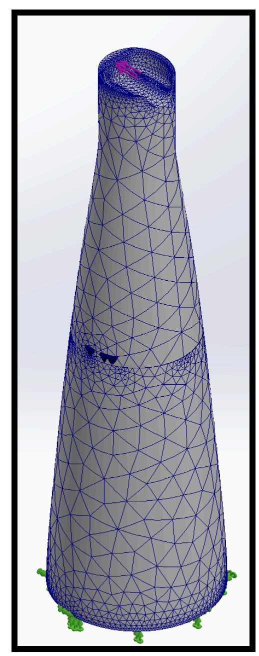


Figure 16c: Tower mesh

Below are the results of the FEA simulation described through the displacement, stress, and safety factor charts given by Solidworks.

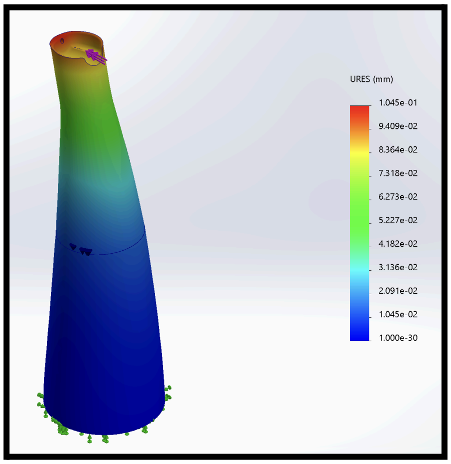
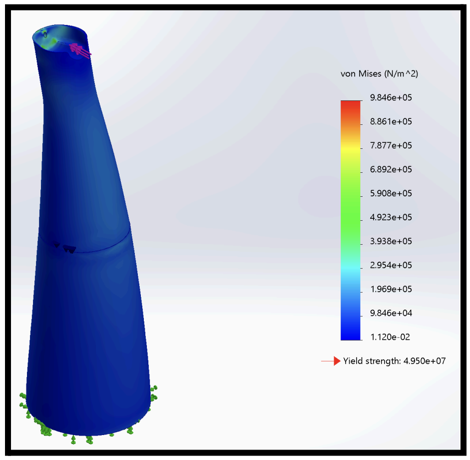
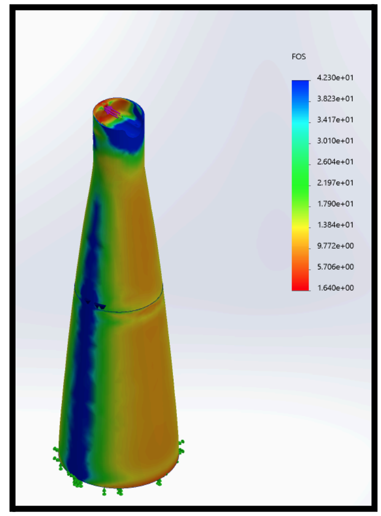
		

Figure 17a: Displacement simulation chart for 9.8 N load. Maximum is 0.1045 mm.	*Figure 17b:* Stress simulation chart for 9.8 N load. Maximum is 0.98 MPa	*Figure 17c:* Factor of safety simulation chart for 300 N load. Min FOS is about 1.64 for this load.

By varying the load from 10 N to 100 N in the FEA simulation, the following results show the simulated variation in displacement. The slope of 70.3 N/mm is the stiffness that is simulated through the deflection simulations.

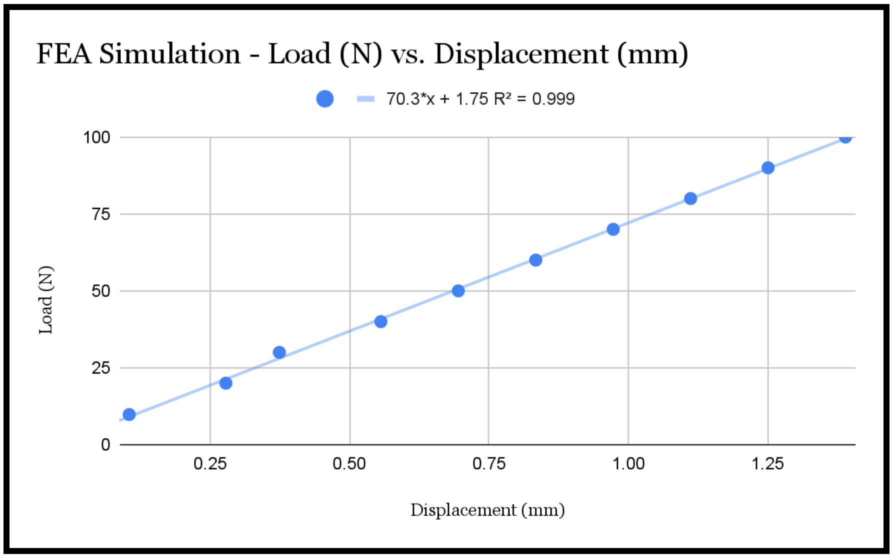


Figure 18: Load vs displacement simulation plotted with a line fitted to the data. Slope of 70.3 represents stiffness in N/mm

The total volume of the tower is shown below through Solidworks' Mass Properties.

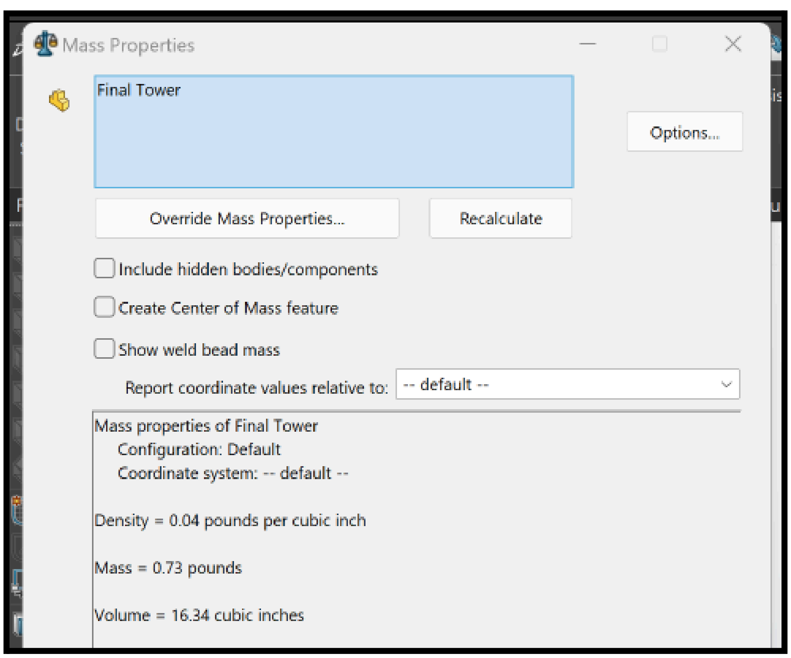


Figure 19: Total volume, 16.34 in^3, of tower through the Mass Properties feature in Solidworks

3D Printing

Below are the sliced configurations through which we printed our tower.

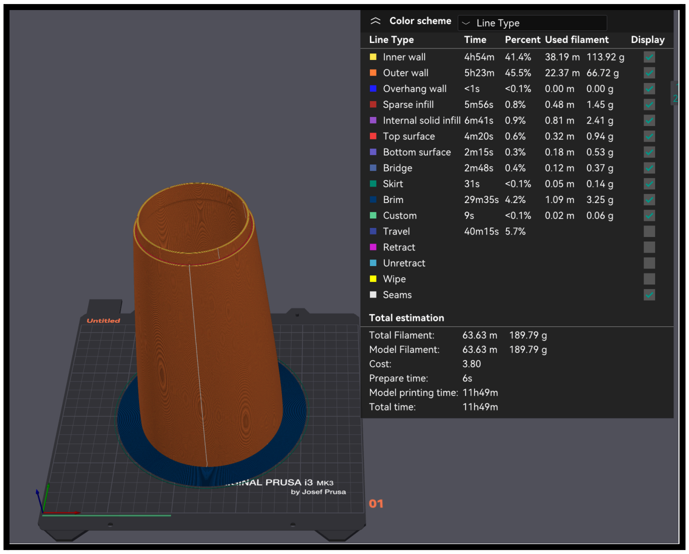


Figure 20: Sliced configuration and print details of print characteristics for tower bottom half.

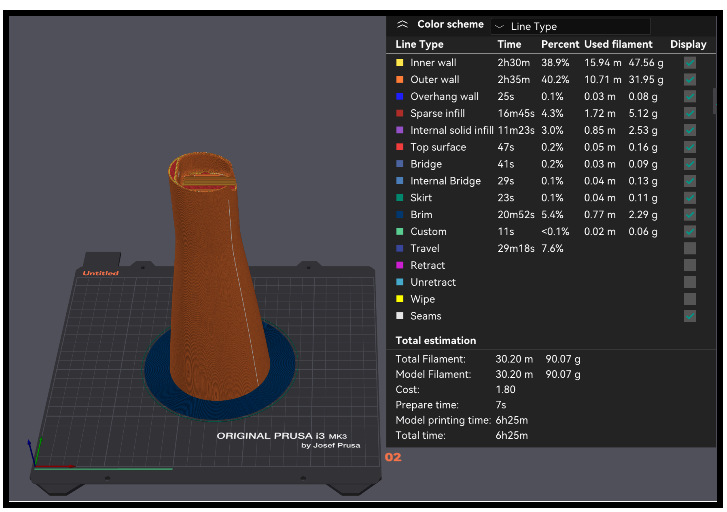


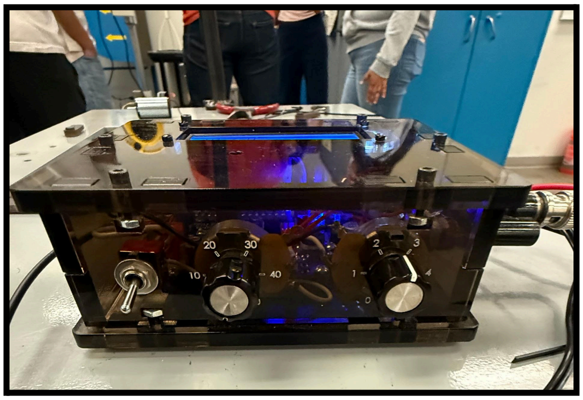
Figure 21: Sliced configuration and print details of print characteristics for tower top half.

The models were sliced with 3 wall loops and 40 percent infill density (because most of the tower is just walls). From these sliced models, the software reports a total mass of filament used equal to 279.86 g. As mentioned earlier, this is quite similar to the ultimate 298.4 grams we weighed.

Testing and Results

Testing Process: Power

The first test was a power test. The equipment used for testing power is presented below.



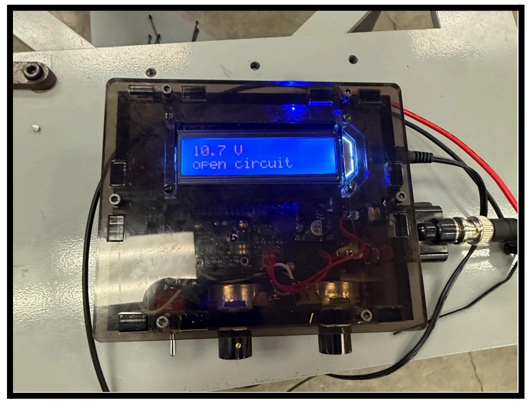


Figure 22a and 22b: Power Meter (Load Box): measures voltage, current, power, and resistance

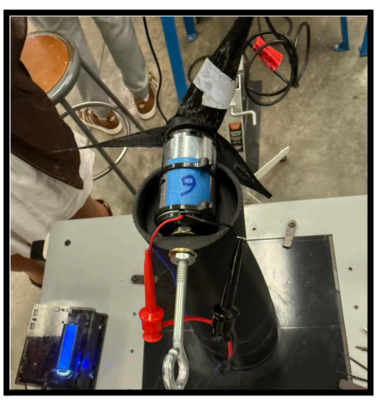


Figure 23: Motor being used as a generator on the windmill

Figure 24: Anemometer: For measuring the wind velocity of the blower in mph

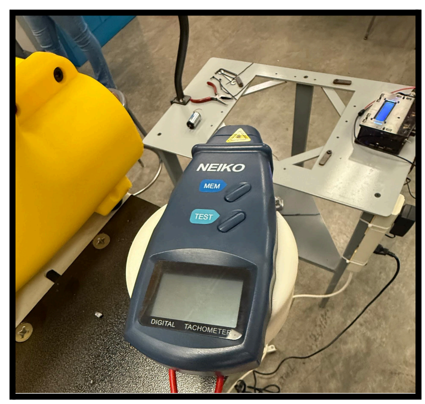


Figure 25: Tachometer: For measuring the rotational speed of the blade in rpm

Power Background Information

Power measurement involves two main components: an electrical meter to measure current, voltage, and power, and a load box (with a potentiometer to vary resistance) to simulate a load drawing power. Electrical power sources (such as wind turbine generators) provide maximum power under certain loading conditions. Whether this maximum power is fully utilized depends on the load. In real wind turbines, a computer-controlled power unit continuously adjusts the load based on wind speed to achieve maximum power output under all conditions at all times.

Procedure

We are asked to determine the maximum output power of our wind turbine generator. To do this, we must search for the optimal load condition by varying the resistance in the circuit. Note: the ideal loading condition varies with wind speed (we do not explore this relationship in this test).

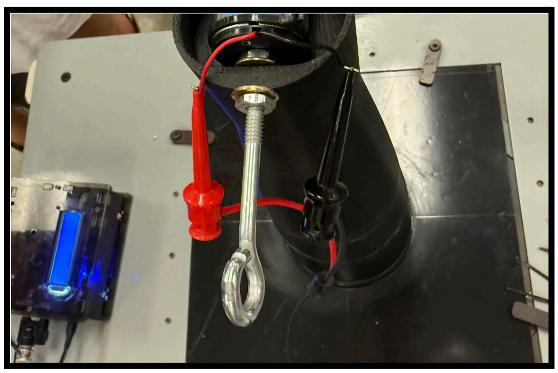
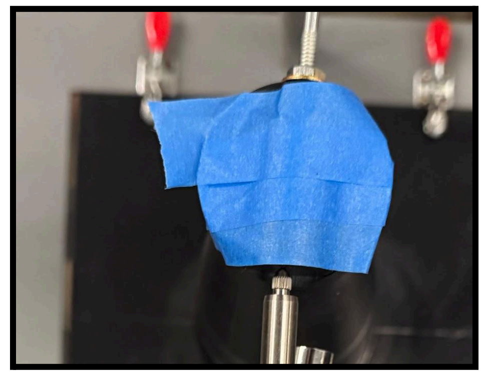
1. Secure the wind turbine to the testing platform and position the blower so that the wind velocity is approximately 25 mph, using an anemometer to ensure accuracy (*Fig. 24*).
2. Turn off the blower and connect the generator and load box to the power meter (*Fig. 22a and 22b*).
3. Using the power meter, zero the potentiometer (turn it fully counterclockwise), then turn the blower on to level 3 (*Fig. 22a*).
4. Gradually turn the potentiometer knob clockwise in small increments. At each step, record the current, voltage, and power. Power will increase, reach a peak, and then begin to drop (*Fig. 22a*).
5. Create a plot of power vs. current to determine the maximum power generated by the wind turbine

Power Results

Efficiency is testing power/theoretical power maximum which is 0.206 W / 9.0838 W, which is 2.87%.

Testing Process: Stiffness

The second test was a stiffness test. The equipment used for testing stiffness is presented below.

		
Figure 26a: Dial Indicator: Measures tower deflection	*Figure 26b:* Eyebolt: Attachment point for the string	*Figure 26c:* Motor Housing: Mounted on the top plate

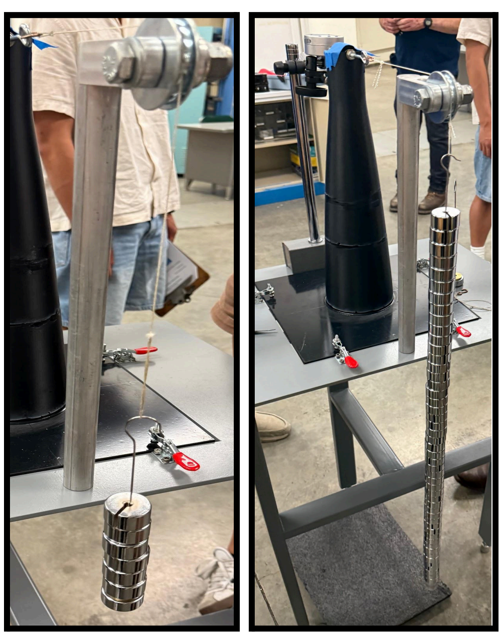


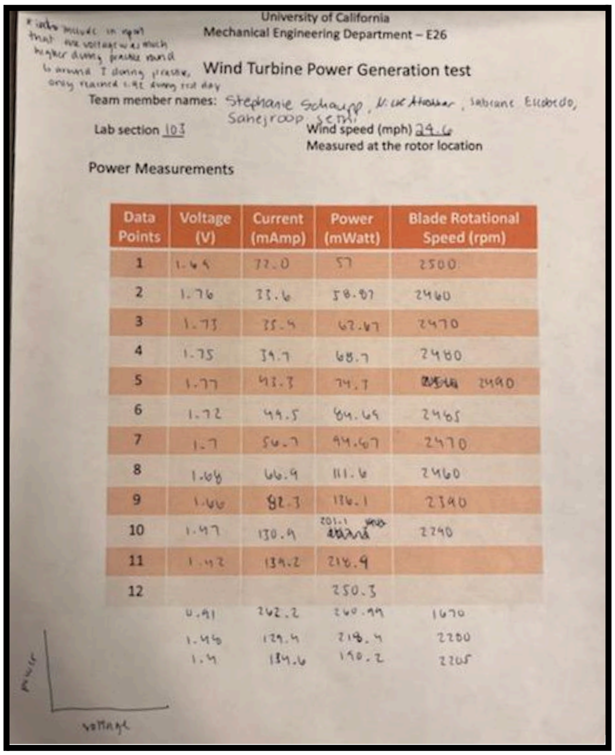
Figure 27a and 27b: Pulley and Weights: Used to apply the load through gravity

Procedure

The stiffness (or deflection resistance) of the wind turbine tower is measured by applying a load to the vertical backing plate that supports the motor, as shown in the setup. A string is attached to the back of the top plate using an eyebolt, passed over a pulley, and connected to hanging weights. A dial indicator is used to measure the deflection of the tower as weights are added.

1. Secure the wind turbine to the testing platform.
2. Attach a string to the back of the top support plate using the provided eyebolt and pull it over the pulley (*Fig. 26b*).
3. Position the dial indicator against the tower and zero it (*Fig. 26a*).
4. Add a 100 g weight incrementally without picking up the weight for each data point (10 data points total) (*Fig. 27a and 27b*).
5. Record the deflection reading from the dial indicator after each weight is added.
6. Plot Load vs. Deflection on a graph. Fit a straight-line curve to the data points.
7. The stiffness of the tower is determined by the slope (k) of the line.

Power and Stiffness Data Tables



University of California
Mechanical Engineering Department – E26

Wind Turbine Power Generation test

Team member names: Stephanie Schaupp, Nicole Atassar, Sabrina Escobedo, Sahejroop Sethi

Lab section 103

Wind speed (mph) 24.6
Measured at the rotor location

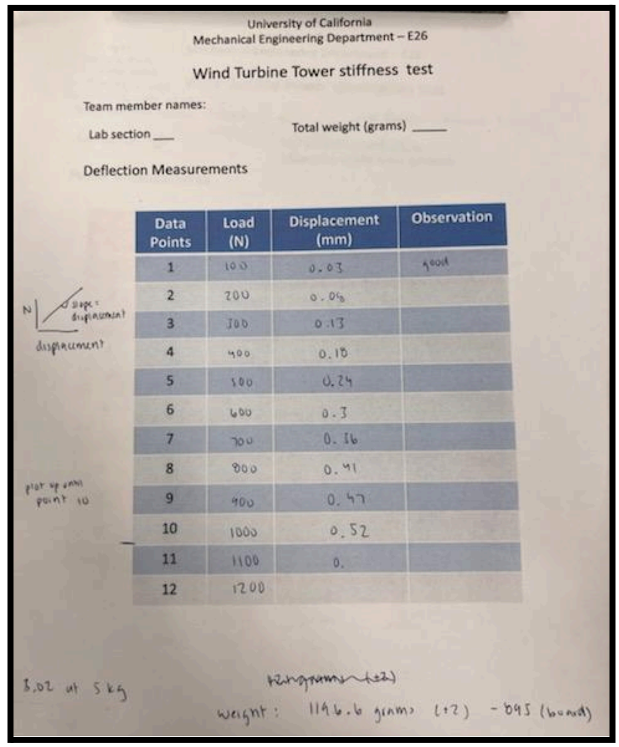
Power Measurements

Data Points	Voltage (V)	Current (mAmp)	Power (mWatt)	Blade Rotational Speed (rpm)
1	1.65	72.0	57	2500
2	1.76	33.6	58.87	2460
3	1.73	35.4	62.47	2470
4	1.75	39.7	68.7	2480
5	1.77	42.3	74.7	2490
6	1.72	49.5	84.65	2465
7	1.7	56.7	94.67	2470
8	1.68	66.9	111.6	2460
9	1.66	82.3	136.1	2390
10	1.47	130.9	201.1	2290
11	1.42	139.2	218.9	
12			250.3	
	0.91	262.2	260.99	1670
	1.46	129.4	218.4	2200
	1.4	184.6	190.2	2205

power

voltage

Figure 28a: Power Measurements



University of California
Mechanical Engineering Department – E26

Wind Turbine Tower stiffness test

Team member names:

Lab section ___

Total weight (grams) _____

Deflection Measurements

Data Points	Load (N)	Displacement (mm)	Observation
1	100	0.03	good
2	200	0.06	
3	300	0.13	
4	400	0.18	
5	500	0.24	
6	600	0.3	
7	700	0.16	
8	800	0.41	
9	900	0.47	
10	1000	0.52	
11	1100	0.	
12	1200		

N

slope = displacement

displacement

plot up until point 10

3.02 at 5 kg

weight: 1196.6 grams (+2) − 895 (board)

Figure 28b: Deflection Measurements

Note: *Clearer versions of the data shown in Figures 28a and 28b are available in digital format in the Appendices section, where values are recorded and visualized using Google Sheets.*

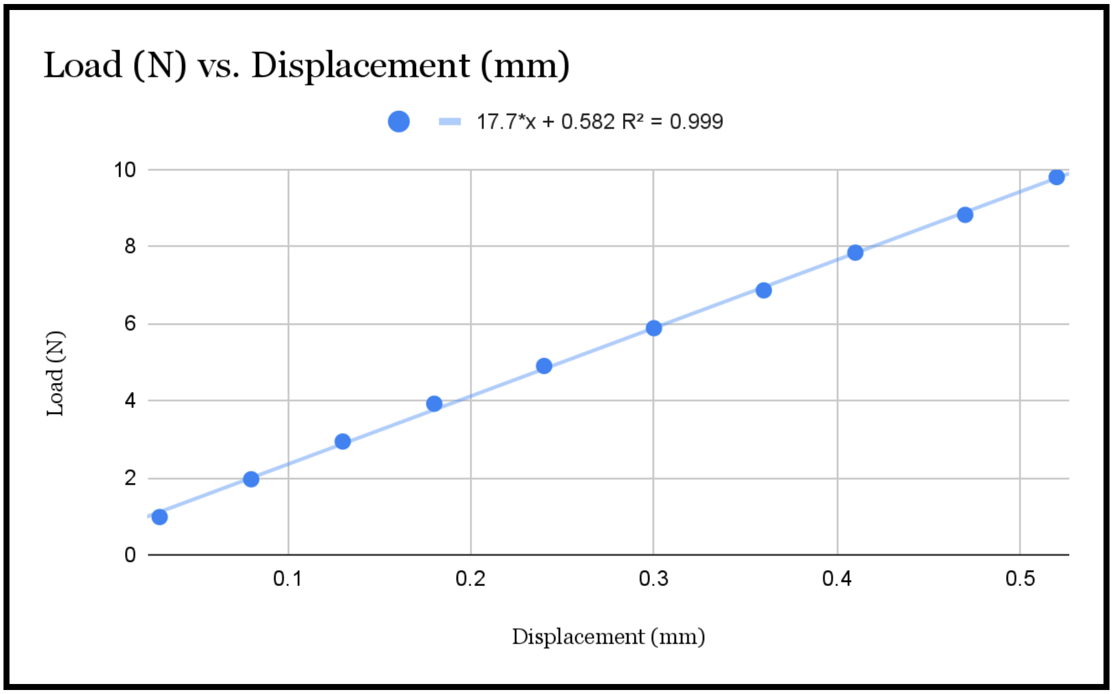


Figure 29: Load vs Displacement Plot (stiffness is 17.7 N/mm)

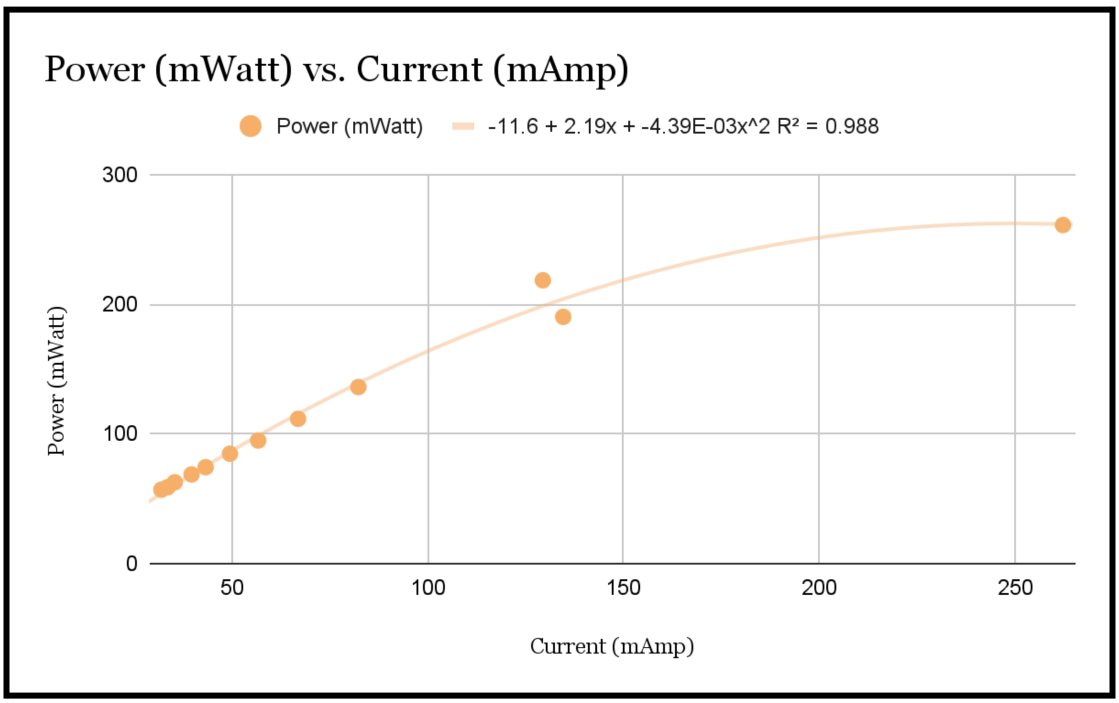


Figure 29: Power vs Current Plot

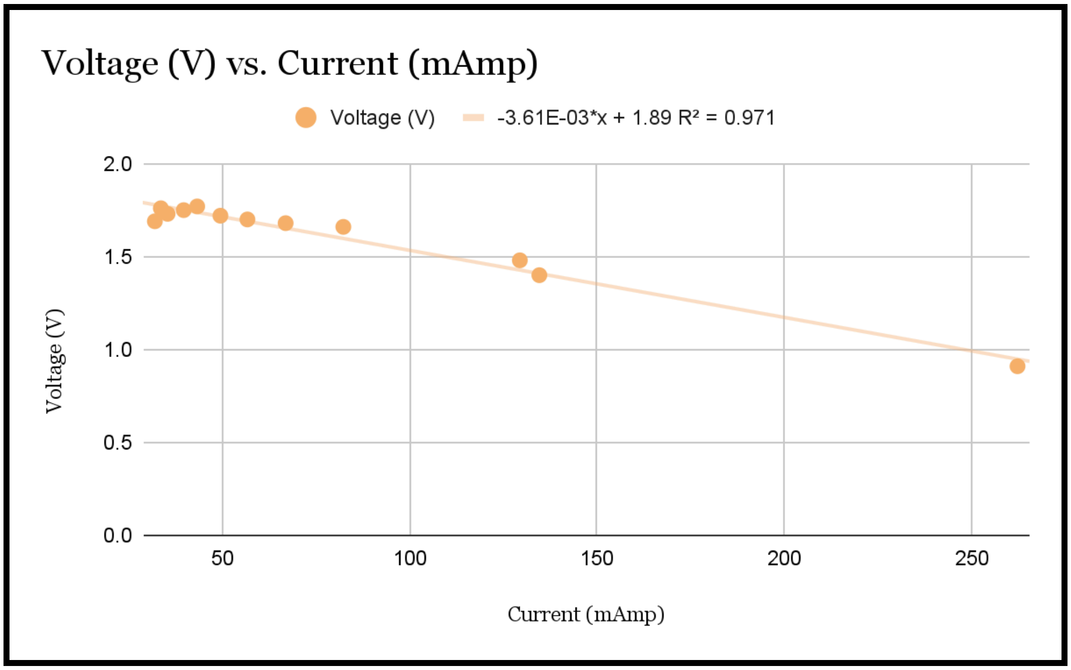


Figure 30: Voltage vs Current Plot

CAD Drawings

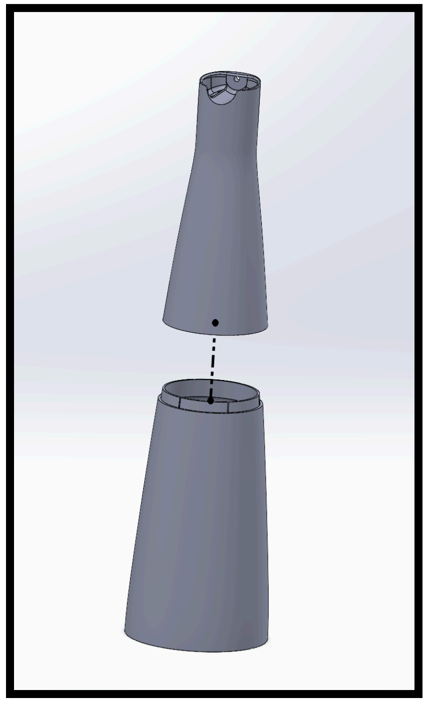


Figure 31: Exploded view of the two-part tower assembly, designed to meet 3D printer size constraints with aligning and bonding features to assist during gluing.

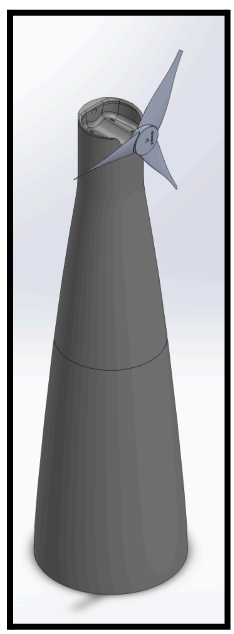


Figure 32: CAD rendering of the fully assembled wind turbine, showing the integrated tower and three-blade rotor configuration.

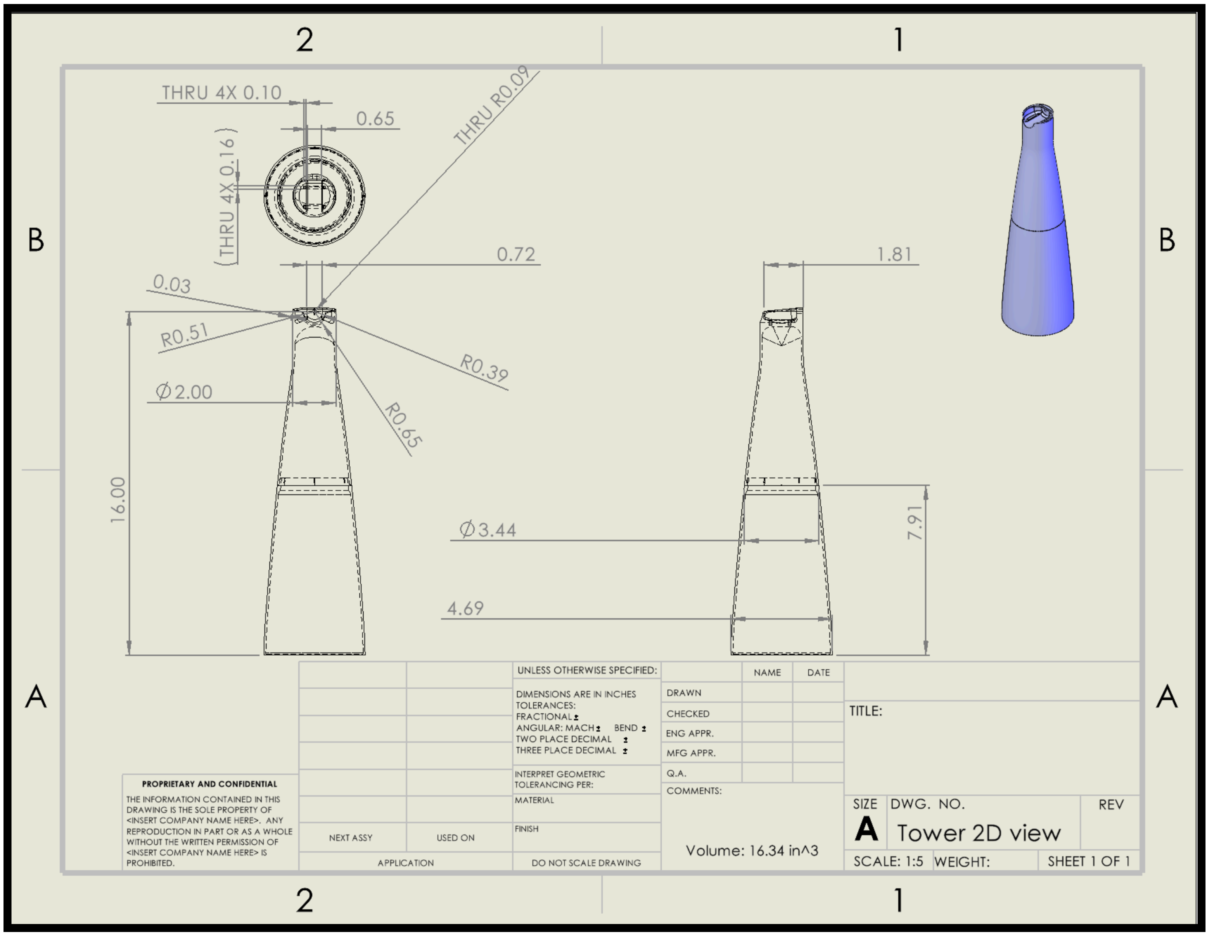


Figure 33: Detailed 2D engineering drawing of the wind turbine tower, showing dimensions and key geometric features for fabrication.

Conclusions

To summarize our design work, we began by researching airfoil profiles for the blade and hand-sketching preliminary schematics for both the blade and tower. We then created CAD models for each component. For manufacturing, we 3D printed both the blade and the tower, printing the tower in two segments and later gluing them together. During testing, we conducted two separate experiments: one to determine the maximum power output of our turbine under standardized lab conditions, and another to measure tower deflection under a 1 kg load.

Our turbine's power output was lower on average compared to other groups, peaking at approximately 260.99 mW. This is significantly lower than what we expected, and the primary reason for this when viewing the blade in slow motion footage is that the blades tips deflected greatly, causing the airfoil shape to not stay the same as the SG 6043 one that we used. This likely resulted in more drag and less lift than intended, reducing the rotation of the blades and thus the power generated.

However, in the structural deflection test, our design performed exceptionally well, with a deflection of only 0.52 mm with a 1kg or 9.8 N load. Based on the plotted results of load vs displacement, this corresponds to a stiffness of 17 This strength was largely due to our cylindrical tower with a cross sectional profile optimized by a program that we wrote. This is quite different from the simulation that we did through FEA, which gave a predicted stiffness of 70 N/mm. The discrepancy between simulation and empirical testing data likely originates from the fact that the adhesive and adhesive stiffness were not simulated (where instead the bonds were simulated as perfectly rigid connections in Solidworks). Additionally, a printing error caused a skipped filament layer in our tower, compromising the one piece it was originally. To address this, we cut the piece at the weak point, sanded it, and re-glued it to reinforce the joint and prevent failure, but this was likely a contributor to a lack of stiffness.

Overall, this project taught us valuable lessons about translating digital designs into physical prototypes, anticipating real-world issues in manufacturing, and implementing creative solutions during testing.

Recommendations for Future Work

If we were to redo the project, we would first perform a stress analysis on the blade prior to printing to evaluate its deformation under wind loading, ensuring that it maintains its optimal aerodynamic shape. This is something we failed to consider in detail in our research and design of the blade. In fact, we had opted to not go with the NACA 65-415 blade because it seemed to have too much excess material, but after our testing, this may have been a benefit rather than a cause of less performance. The process for doing this would be to determine the force imparted on the blades with 25 mile per hour winds, and determine the effective force we can approximate this to be at the tip of each blade. Either using conventional beam bending equations as a rough check or using Solidworks FEA, we would then validate that the deflection is not greater than around a millimeter, such that the blade retains its shape and performance is not curbed due to deformation, as our blade was.

For our tower, we had originally limited the optimization program we wrote so that the minimum thickness of the tower was equivalent to the thickness of 5 walls (2.25 mm) of the filament with 0.2 mm layer height. However, it may be possible to push this number lower, such that we set it to only 2 or 3 walls. This would allow a larger maximum radius at the base while still meeting the volume constraint because of less volume needed for every ring of material in the tower. Another possible direction to explore is the direction of printing. Given our tapered cylindrical design, it was difficult to print with the tower lying down (this would require a lot of support material), but this approach would load the filament fibers in tension and compression rather than loading the bond between the layers. This may be one way to significantly increase the stiffness and minimize deflection, as the highly anisotropic nature of 3D prints suggests different performance based on print orientation. Yet another direction to explore would be modifying the cross section of the tower to one that is more optimized for uniaxial loading. Currently, it is circular, which has a good second moment of area, but one way to improve upon the stiffness would be to go with a more rectangular cross section or something similar to an I-beam. Because these cross sections do a slightly better job at placing material away from the bending neutral axis, this would be a potentially more efficient use of material.

These changes would not only address the issues noticed during testing, with the blade bending and a heavier tower, but also improve the turbine performance and material efficiency, which is vital if the prototype were to be translated into real-world applications.

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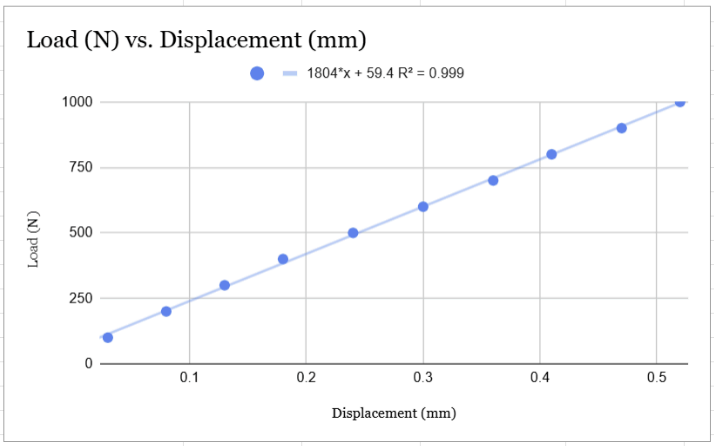
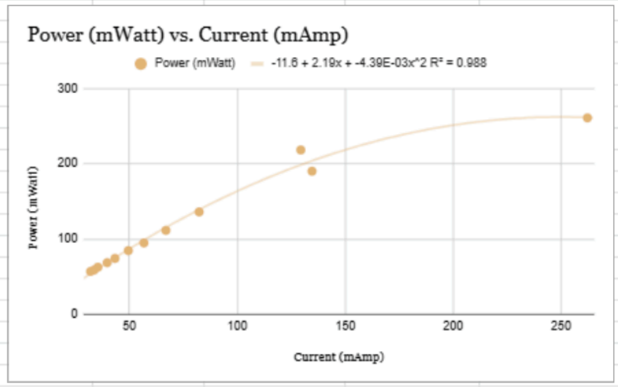
Appendices

Deflection Measurements	Data Points	Load (N)	Displacement (mm)	Observation
	1	100	0.03	
	2	200	0.08	
	3	300	0.13	
	4	400	0.18	
	5	500	0.24	
	6	600	0.3	
	7	700	0.36	
	8	800	0.41	
	9	900	0.47	
	10	1000	0.52	



Power

# Data Points	Voltage (V)	Current (mAmp)	Power (mWatt)	Blade Rotational Speed (rpm)
1	1.69	32	57	2500
2	1.76	33.6	58.87	2460
3	1.73	35.4	62.67	2470
4	1.75	39.7	68.7	2480
5	1.77	43.3	74.3	2490
6	1.72	49.5	84.69	2485
7	1.7	56.7	94.87	2470
8	1.68	66.9	111.6	2460
9	1.66	82.3	136.1	2390
10	0.91	262.2	260.99	1670
11	1.48	129.4	218.4	2280
12	1.4	134.6	190.2	2205



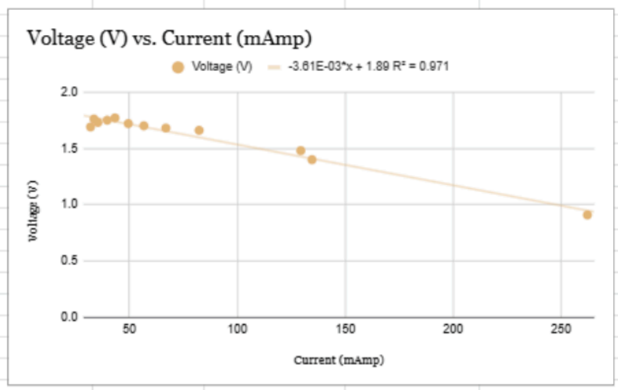


Figure A1: Experimental data collected and analyzed using Google Sheets; left side displays deflection measurements, showing a linear relationship between applied load (N) and tower displacement (mm), indicating structural stiffness.[1]

Figure A2: Right side presents electrical performance data, with graphs showing power output (mW) and voltage (V) as functions of current (mA).[1]

1 https://docs.google.com/spreadsheets/d/17lymiQM__4C75OpjmzywfY2hopo0qfFJbBB5vN1vedw/edit?usp=sharing

Load (N)	Displacement (mm)
9.8	0.1045
20	0.278
30	0.374
40	0.5561
50	0.6951
60	0.8341
70	0.9731
80	1.112
90	1.251
100	1.39

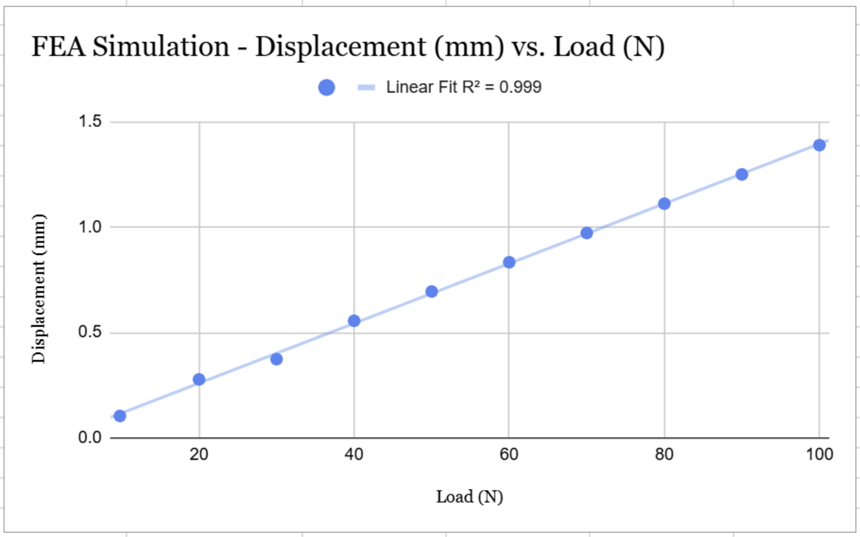


Figure A3: Graphical output from the FEA simulation used to evaluate how the tower structure deforms under increasing applied loads.[1]

[1] https://docs.google.com/spreadsheets/d/17lymiQM__4C75Opjmzywfy2hopo0qfFJbBB5vN1vedw/edit?usp=sharing

```python
import numpy as np
import matplotlib.pyplot as plt
from mpl_toolkits.mplot3d import Axes3D
from scipy.optimize import minimize
from scipy.interpolate import make_interp_spline
import ezdxf

def second_moment_area(R, T):
   return (np.pi / 4.0) * (R**4 - np.clip(R - T, 0.0, None)**4)

def cross_section_area(R, T):
   return np.pi * (R**2 - np.clip(R - T, 0.0, None)**2)

def beam_deflection(R_vals, T_vals, P, E, L):
   N = len(R_vals)
   dx = L / N
   x_mid = (np.arange(N)+0.5)*dx
   I_vals = second_moment_area(R_vals, T_vals)

   integrand = (L - x_mid)**2 / I_vals
   return (P/E)*np.sum(integrand)*dx

def beam_volume(R_vals, T_vals, L):
   N = len(R_vals)
   dx = L / N
   A_vals = cross_section_area(R_vals, T_vals)
   return np.sum(A_vals)*dx

def smoothness_penalty(R_vals, alpha=1.0):
   diff = np.diff(R_vals)
   return alpha * np.sum(diff**2)

def combined_objective(vars, N, P, E, L, alpha):
   R_vals = vars[:N]
   T_vals = vars[N:]
   defl = beam_deflection(R_vals, T_vals, P, E, L)
   smth = smoothness_penalty(R_vals, alpha)
   return defl + smth

def last_x_distance_change_constraint(x, N, L, x_dist, dR_max):
   R_vals = x[:N]

   dx = L / N
   x_mid = (np.arange(N) + 0.5)*dx

   i0 = np.searchsorted(x_mid, L - x_dist, side='left')

   sum_diff = 0.0
   for i in range(i0, N-1):
       sum_diff += abs(R_vals[i+1] - R_vals[i])

   return dR_max - sum_diff
```

```python
def make_constraints(N, L, V_max, x_dist, dR_max):
   cons = []

   def volume_constraint(v):
       R_vals = v[:N]
       T_vals = v[N:]
       vol = beam_volume(R_vals, T_vals, L)
       return V_max - vol  # must be >= 0

   cons.append({'type': 'ineq', 'fun': volume_constraint})

   def radial_constraint_i(i, v):
       R_vals = v[:N]
       T_vals = v[N:]
       return R_vals[i] - T_vals[i]

   for i in range(N):
       cons.append({'type': 'ineq',
                    'fun': lambda vv, i=i: radial_constraint_i(i, vv)})

   def last_change_constr(v):
       return last_x_distance_change_constraint(v, N, L, x_dist, dR_max)

   cons.append({'type': 'ineq', 'fun': last_change_constr})

   return cons

def build_feasible_initial_guess(N, L, R_max, R_min, T_min, V_max):
   x_array = np.linspace(0, 1, N)
   R_linear = R_max - (R_max - R_min)*x_array
   T_linear = np.full(N, T_min)

   dx = L / N
   def cross_area(Ri, Ti):
       return np.pi*(Ri**2 - max(Ri - Ti, 0.0)**2)

   vol_guess = 0.0
   for i in range(N):
       vol_guess += cross_area(R_linear[i], T_linear[i])*dx

   if vol_guess>V_max:
       scale_factor = np.sqrt(V_max/vol_guess)
       R_scaled = R_min + (R_linear - R_min)*scale_factor
   else:
       R_scaled = R_linear

   R_scaled = np.maximum(R_scaled, T_min)
   R_scaled = np.maximum(R_scaled, R_min)

   return R_scaled, T_linear

def create_spline_points(x_mid, r_data, L, n_points=200):
   from scipy.interpolate import make_interp_spline
```

```
    x_spline = np.concatenate(([0.0], x_mid, [L]))
    r_spline = np.concatenate(([r_data[0]], r_data, [r_data[-1]]))

    spline = make_interp_spline(x_spline, r_spline, k=3)
    x_eval = np.linspace(0, L, n_points)
    r_eval = spline(x_eval)
    return x_eval, r_eval

def export_spline_dxf(file_name, x_vals, y_vals, layer_name="Spline"):
    doc = ezdxf.new(dxfversion='R2010')
    msp = doc.modelspace()
    points = [(float(x_vals[i]), float(y_vals[i])) for i in range(len(x_vals))]
    msp.add_spline(fit_points=points, dxfattribs={'layer': layer_name})
    doc.saveas(file_name)

def generate_spline_profiles(x_mid, R_opt, T_opt, L, prefix="beam_spline"):
    x_outer, r_outer = create_spline_points(x_mid, R_opt, L, n_points=200)

    r_inner_raw = R_opt - T_opt
    r_inner_clamped = np.clip(r_inner_raw, 0.0, None)
    x_inner, r_inner = create_spline_points(x_mid, r_inner_clamped, L, n_points=200)

    outer_file = f"{prefix}_outer_spline.dxf"
    inner_file = f"{prefix}_inner_spline.dxf"

    export_spline_dxf(outer_file, x_outer, r_outer, layer_name="OuterRadius")
    export_spline_dxf(inner_file, x_inner, r_inner, layer_name="InnerRadius")

    print(f"Spline DXF exported:\n  {outer_file}\n  {inner_file}")


def plot_results(R_opt, T_opt, L):

    N = len(R_opt)
    dx = L / N
    x_mid = (np.arange(N) + 0.5)*dx

    fig, ax = plt.subplots()
    ax.plot(x_mid, R_opt, label="Outer R")
    ax.plot(x_mid, T_opt, label="Thickness")
    ax.set_xlabel("x [m]")
    ax.set_ylabel("[m]")
    ax.grid(True)
    ax.legend()
    ax.set_title("Optimized Radius & Thickness")

    fig3d = plt.figure()
    ax3d = fig3d.add_subplot(111, projection='3d')
    ax3d.set_title("3D Tube Visualization")
    ax3d.set_xlabel("X [m]")
    ax3d.set_ylabel("Y [m]")
    ax3d.set_zlabel("Z [m]")

    theta = np.linspace(0, 2*np.pi, 40)
    X_2D, TH_2D = np.meshgrid(x_mid, theta)
```

```
    R_outer_2D = np.tile(R_opt, (len(theta),1))
    Y_outer = R_outer_2D*np.cos(TH_2D)
    Z_outer = R_outer_2D*np.sin(TH_2D)
    ax3d.plot_surface(X_2D, Y_outer, Z_outer, color='blue', alpha=0.6, edgecolor='none')

    R_inner_1D = np.clip(R_opt - T_opt, 0, None)
    R_inner_2D = np.tile(R_inner_1D, (len(theta),1))
    Y_inner = R_inner_2D*np.cos(TH_2D)
    Z_inner = R_inner_2D*np.sin(TH_2D)
    ax3d.plot_surface(X_2D, Y_inner, Z_inner, color='red', alpha=0.4, edgecolor='none')

    plt.show()

def run_optimization(alpha_smooth=0.1, x_dist=0.05, dR_max=0.01):

    # params
    L = 0.4064
    P = 1000.0
    E = 4.0e9
    V_max = 0.00027858*0.8
    N = 100

    R_max = 0.1143
    R_min = 0.0508/2
    T_max = 0.1143
    T_min = 0.00225

    R_init, T_init = build_feasible_initial_guess(N, L, R_max, R_min, T_min, V_max)
    x0 = np.concatenate([R_init, T_init])

    bnds = []
    for i in range(N):
        bnds.append((R_min, R_max))
    for i in range(N):
        bnds.append((T_min, T_max))

    cons = make_constraints(N, L, V_max, x_dist, dR_max)

    result = minimize(
        fun=lambda v: combined_objective(v, N, P, E, L, alpha_smooth),
        x0=x0,
        method='SLSQP',
        bounds=bnds,
        constraints=cons,
        options={'ftol':1e-12, 'maxiter':2000, 'disp':True}
    )

    if result.success:
        print("Optimization successful!")
        print(f"Final combined objective = {result.fun:.6g} (deflection + penalty)")
        R_opt = result.x[:N]
        T_opt = result.x[N:]

        defl = beam_deflection(R_opt, T_opt, P, E, L)
```

```
        print(f"Final deflection = {defl:.6g}")

        vol = beam_volume(R_opt, T_opt, L)
        print(f"Final volume = {vol:.6g} / {V_max:.6g} (ratio={vol/V_max:.3f})")

        x_mid = (np.arange(N)+0.5)*(L/N)
        i0 = np.searchsorted(x_mid, L - x_dist, side='left')
        sum_diff = sum(abs(R_opt[i+1] - R_opt[i]) for i in range(i0, N-1))
        print(f"Total R-change in last {x_dist} m = {sum_diff:.6g} (limit={dR_max})")

        plot_results(R_opt, T_opt, L)

        generate_spline_profiles(x_mid, R_opt, T_opt, L, prefix="beam_spline")

        print(R_opt)
    else:
        print("Optimization failed.")
        print(result.message)

    return result

run_optimization(alpha_smooth=7, x_dist=0.0762*1.25, dR_max=0.01)
```

Figure/Code A4: Code written to optimize the profile of the tower.