E26 Three-Dimensional Modeling Final Report

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May 5, 2023

Project Summary

The primary goal of this project was to research the structural details behind wind turbines and determine which avenues to take in designing our own. As a group, we worked together to prioritize specific structural capabilities, design a 3-D wind turbine encompassing those structural priorities, print the wind turbine, and finally test its power and stiffness to determine whether our design effectively replicates a wind turbine. Some benchmark requirements our tower had to achieve was a 16-inch height from the bottom of our 12 x 12-inch base platform to the center of the motor shaft alongside a maximum blade radius of 3 inches and a maximum volume of 17 cubic inches. Given that the 3D printer we were using only had a 9 x 9 x 9-inch footprint, we had to print the bottom and top half of the tower separately and glue them together afterwards.

Our research led us to believe that our tower structure would be most effective if modeled using a lattice structure. This would allow us to prioritize stability without exceeding our maximum volume limit and allow more mechanisms of distributing the downward force coming from the weight of the top half of the turbine and the strong wind. We also decided on three blades for our final design as, even disregarding real-life costs, three blades give the best balance of power efficiency and stability.

After testing, we discovered that our tower ended up weighing 233g and was capable of handling a more significant load of 5 kg while deflecting 3.74 mm; at 1 kg, our tower only had a deflection of 0.79 mm. Our tower met all design restrictions and requirements and ultimately had an overall stiffness of 11571N/m. The turbine's maximum power of 1700 mW occurred when the

rotor recorded a blade speed of 6060 rpm. Throughout the testing process, the group never ran into any significant roadblocks or failures mirrored in the relatively high-performance results we received.

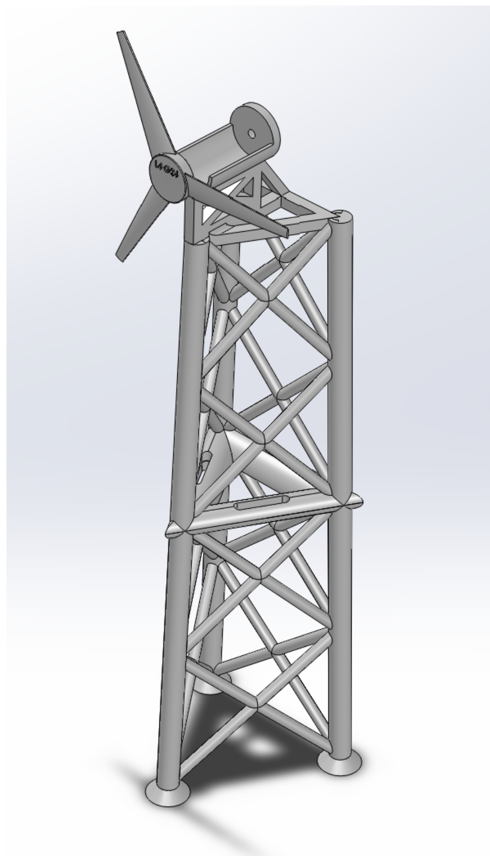

Figure 1

An isometric view of the final tower design post-modeling in SolidWorks

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1. Introduction

With an increasing need for clean energy sources, scientists and engineers have spent the past decade revolutionizing energy collection and storage with the mass introduction of solar, hydro, and electric power. One of the most prominent developments is the mainstream introduction of wind power. In 2021, it was reported that wind power made up just over 6.5% of the world's total energy production–a full 5% increase since 2010–and it is only expected to increase as we shift away from fossil fuels (Fernández, 2019). Capturing wind energy with wind turbines was the aim of this project. This report examines the methods we took to design and test an efficient wind turbine that was both stable and a reliable source of energy generation.

Wind turbines can face upwind or downwind and are designed specifically for either scenario. They operate by allowing the wind to turn the rotors which, through its connection to the generator through a central shaft, spins the generator and creates electricity (DoE, 2019). When designing a wind turbine, certain sacrifices have to be made during the design process. Designing the blades to be larger would generate more power per area swept but would increase the drag and rotor speed of the blade. Other tradeoffs we considered as a group were power versus stability and the number of blades we should use for the rotor.

The tower design was crucial for stability, but we had to be mindful of our volume limit, prohibiting us from designing a completely solid, stable tower. Instead, we opted for a lattice structure due to its structural capabilities and smaller volume. A lattice structure carries many benefits when 3-D printing. 3-D-printed lattices are high-strength yet lightweight arrangements that occupy large spaces with low material use. Lattices also allow more control over shock absorption and impact control, a crucial factor for deflection testing.

Figure 2 shows the point of junction that we chose to split the tower in two. As mentioned in the project summary, our 16-inch height requirement and 9-inch height of the printing footprint made it so that we had to print our tower out in two separate parts and then glue them together after; we also differentiated between the motor mount and the top of the central tower.

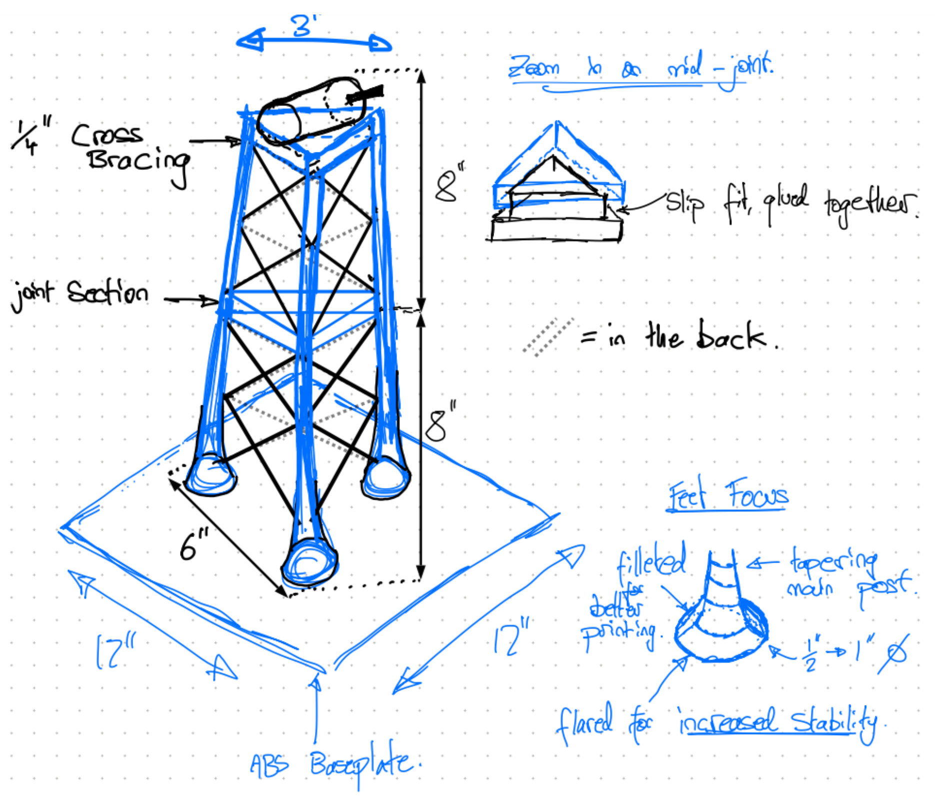


Figure 2

Hand drawn initial design for the tower base and motor cross bracing support

We opted for legs that were both fileted and flared to increase the tower's stability when glued to the ABS baseplate. These legs offer more aerodynamic standing points for the tower, allowing wind to move around them. Mounting the rotor blades in line with one of the tips of the triangle allows the tower to naturally cut the wind in half and push each half on either side of the tower. This process allows for less stress on the turbine due to wind force, increasing stability.

2. Design

2.1 Tower and Rotor Design Process

2.1.1 Blade Design

Blade Profile: NACA 63-415

Vendan's analysis of a wind turbine blade profile finds that "The NACA 63 series…[has] good low speed characteristics with a minimum compromise from consideration of the high speed characteristics"

This airfoil has a relatively high maximum lift coefficient, which means it can generate a lot of lift force for a given angle of attack. Additionally, the airfoil has a smooth and gradual stall behavior, which means that it can maintain lift even at high angles of attack, reducing the risk of blade stall and improving the overall performance of the turbine.

As a group, we thought we should use the NACA 63-415 profile due to its widespread use in industry, relatively easy-to-construct profile, and high performance.

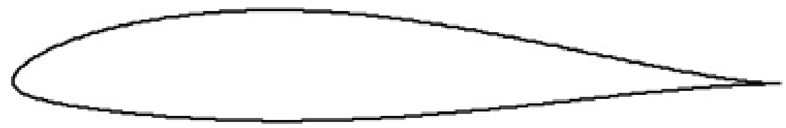
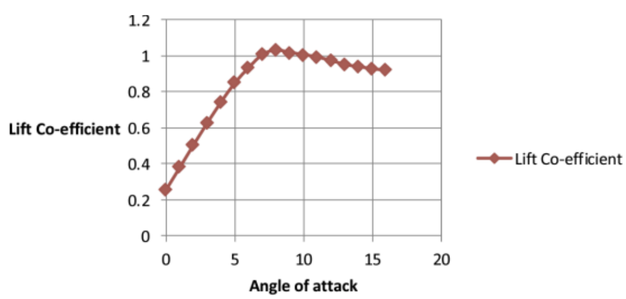


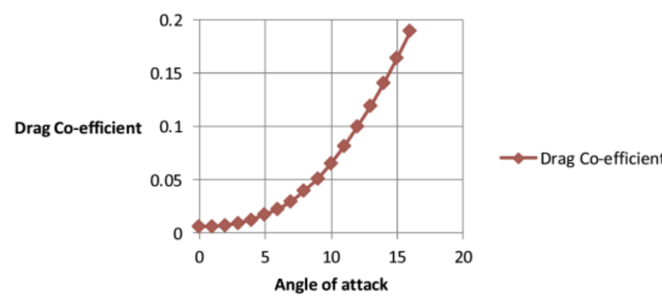
Figure 3

Naca 63-415 Airfoil created from JavaFoil

Angle of Attack: 6-8°

At lower wind speeds, the optimal angle of attack is typically higher, since a higher angle of attack can generate more lift force and increase the efficiency of the turbine. However, as wind speeds increase, the optimal angle of attack decreases, since a lower angle of attack reduces drag and prevents the blade from stalling. A CFD analysis of small profile, horizontal wind turbine blades done by the Journal of Renewable and Sustainable energy(Hosseini, S. M., & Sheldahl, R. E., 2013) produced the results seen below and so to minimize drag and maximize lift we decided on an angle of attack between 6-8 degrees.





Figures 3 & 4

CFD analysis of small profile wind turbine blades looking at drag and lift

Number of Blades: 3

According to “The Effect of the Number of Blades on the Efficiency of A Wind Turbine,” “the efficiency of three-blade turbines is approximately 51%, whereas it is reported to be 49%

for two-blade turbines” (Adeyeye, 2021). As discussed in the lecture, turbines with an even number of blades are unstable. Although studies indicate that having more blades, such as five, can enhance turbine effectiveness, turbines with three blades are simpler to produce and significantly less expensive.

Blade Profile Twist: 17.5°

Professor Youssefi states in lecture that the rotor blade must be twisted to achieve an optimal angle of attack throughout the length of the blade. The article “Effect of Twist Angle of the Blade on the Performance of Power Output of the Horizontal Axis Wind Turbines” emphasizes the importance of a blade built with a twist along its length, as “the closer to the tip of the blade you get, the faster the blade is moving through the air and so the greater the apparent wind angle is (Tawade, 2015). Thus the blade needs to be turned further at the tips than at the root.” In “Design of a Tapered and Twisted Blade…(Giguere & Selig, 1999), researchers examined various twist angles. The conclusion drawn was that 14.9° was optimal. However, other articles suggest a wide range of twist angles, from 10° - 20°, with 17.5° being the most common (Tutorials, 2022).

Blade Length: 6”

To maximize power generation, the longer the blade, the better. Therefore the diameter across the swept area of the three blades should be the maximum allowed, which is 6”.

With the research complete, modeling the blade in CAD was a trivial matter. We first drew a sketch on the provided inner hub of our desired blade profile (one side had to be flat by regulation) and then another on an offset reference plane 3” away form the center axis. The one on the reference plane was created simply by deriving a sketch from the one at the hub, shrinking it down, and rotating it by the blade twist angle - 17.5 degrees in our case. From there a simple loft between the two sketches was done, followed by a fillet on the edges of the blade. We then used the circular pattern command to copy the blade two more times before embossing our group number on the top.

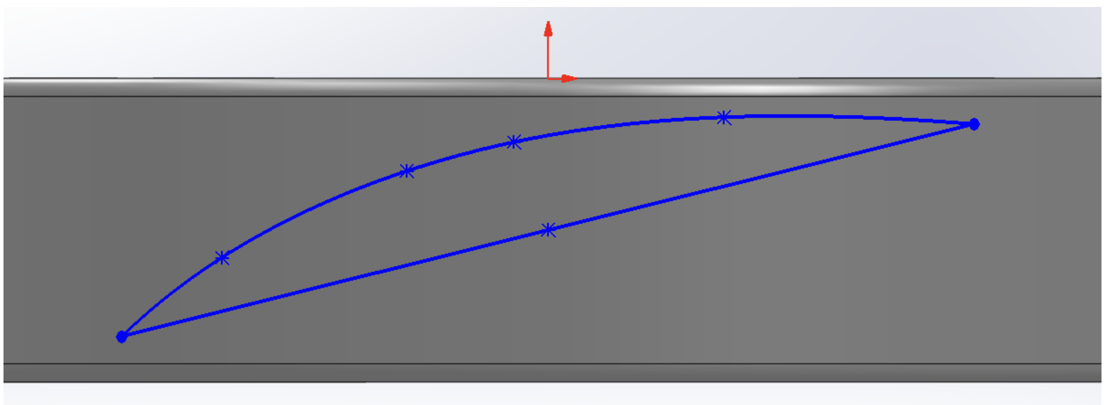


Figure 5

Final Blade Profile Sketch (on hub)

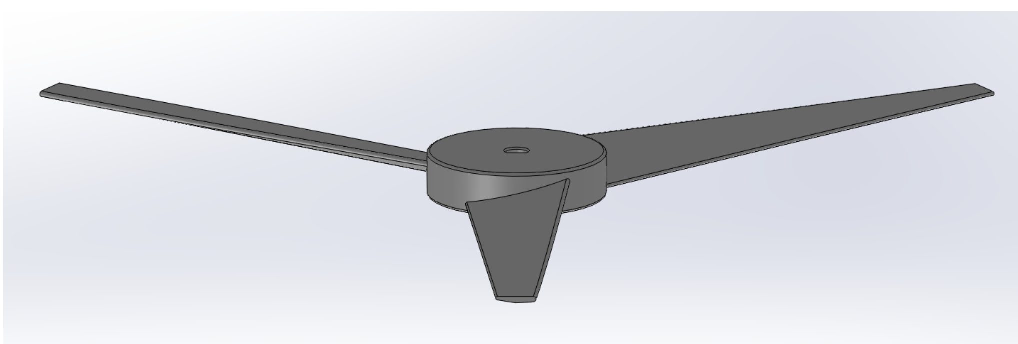


Figure 6

Full Rotor View

2.1.2 Tower Design

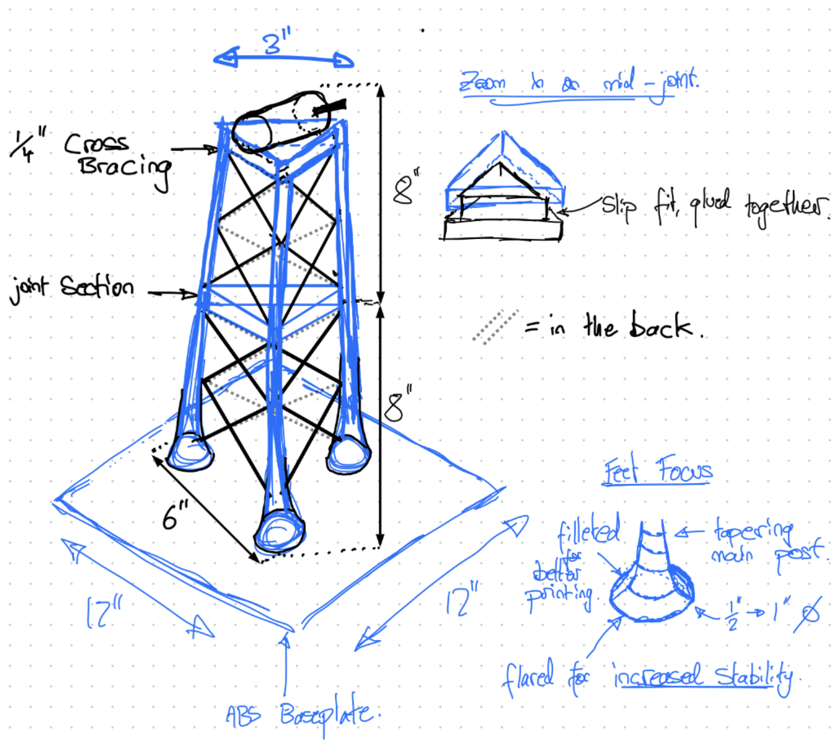


Figure 7

Preliminary tower design sketches

In designing the tower, we had two principal objectives. These were minimizing wind flow disruption around the tower and ensuring maximal stability while minimizing tower volume and area. We found the best way to do this was through a truss structure. We increased the base width using long, thin beams for excellent stability. This also allowed air to pass through undisrupted, reaching the maximum allowed tower height while remaining within the volume constraints.

To be able to print the tower, we split it into three parts and used interlocking design features both in the central split and for the top motor mount to make gluing easier.

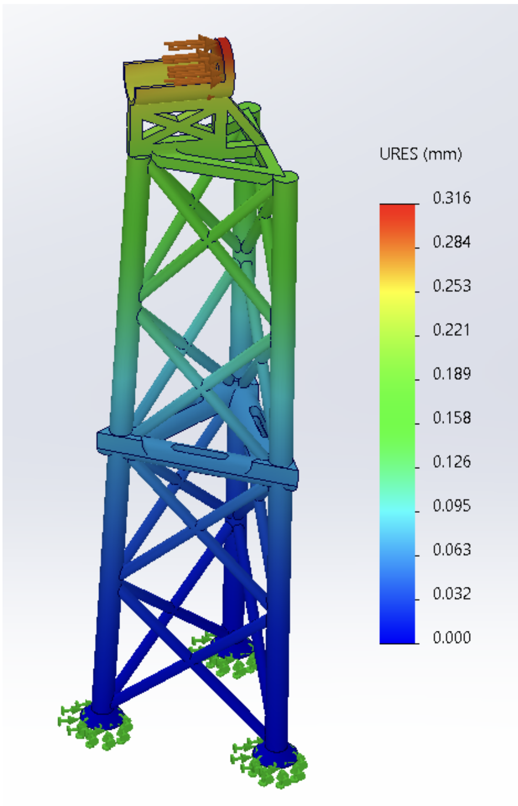
Finally, we used a flared foot design to simplify gluing the tower to the base while ensuring sufficient stability and strength. This maximizes the surface area in contact with the base. We connected the base with filets to the principal truss structures to prevent delamination while 3D printing.

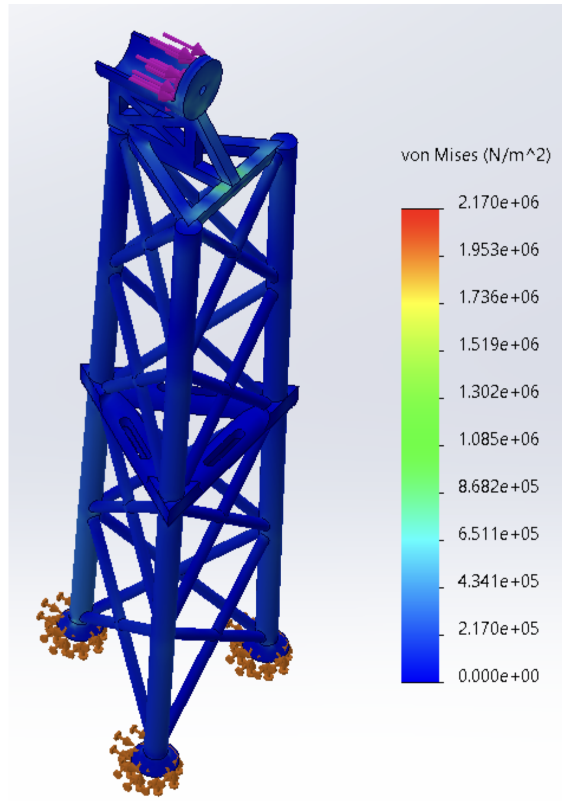
2.2 Design Tools Used

Aside from the numerous sketch iterations produced by different group members, the principal design tool used was the 3D-modeling software Solidworks. Solidworks uses a parametric feature-based design approach to model components, emphasizing ease of use while maintaining high functionality.

To design the tower body, a 3D sketch of the entire structure was drawn, after which many sweeps of varying widths were used to ‘solidify’ the model. A split was introduced in the middle to allow for 3D printing, and filets were added to prevent layer delamination. The motor holder was much simpler to design, needing only three 2D sketches and a couple of extrusion features.

2.3 FEA Simulation





Figures 8 & 9

FEA Plot results of deflection (left) and stress (right) simulations on the tower

Performing FEA on the tower was slightly more complex than initially expected.

This was because the model had a couple of geometrically problematic areas with knife edges and vertices and edges that were too short. This meant we had to use the geometry analysis tool and then extrude large, easily meshable features through the problem patches to simulate the model.

After that, we set the three feet as fixed points and simulated a 9.81N (1kg) load on the rear of the motor basket at the top of the tower before running the study.

The results can be seen above. Regarding the deflection test, the model flexed the most at the top of the motor basket, moving a predicted 0.316mm. It is the least supported area of the tower, so this result makes sense. The deflection decreases uniformly down the tower, with practically none seen at the feet.

In the stress test, most of the model suffered practically no stress except for the tower's top section, where a truss connects to the motor basket. Even here, the stress was minimal, peaking at around 8e+05 N/m2. Most of the force being applied to the tower passes through that truss and then onto the top, so this result also makes sense.

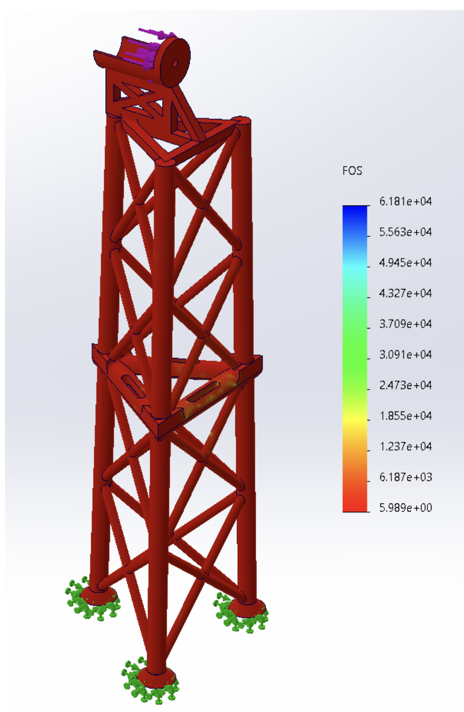


Figure 10

FEA Factor of Safety Plot

Simulating the factor of safety also proved more troublesome than initially expected. The issue here was that Solidworks has no value for the yield strength of ABS in its material database for some reason. Hence, the material had to be manually edited using an average yield strength of ABS found online before running the study. The model safely passed, with most of it having a FOS of around six or just above, with parts of the central horizontal beam having it significantly higher than that at around 3e+04.

2.4 Deflection Analysis

Force (N)	**Simulated Deflection (mm)**	**Measured Deflection (mm)**
0.98	0.032	0.03
1.96	0.063	0.11
2.94	0.095	0.19
3.92	0.126	0.28
4.9	0.158	0.35
5.88	0.189	0.46
6.86	0.221	0.53
7.84	0.252	0.62
8.82	0.285	0.7
9.8	0.316	0.79

Figure 11

Deflection data from real-world testing & Solidworks FEA simulation

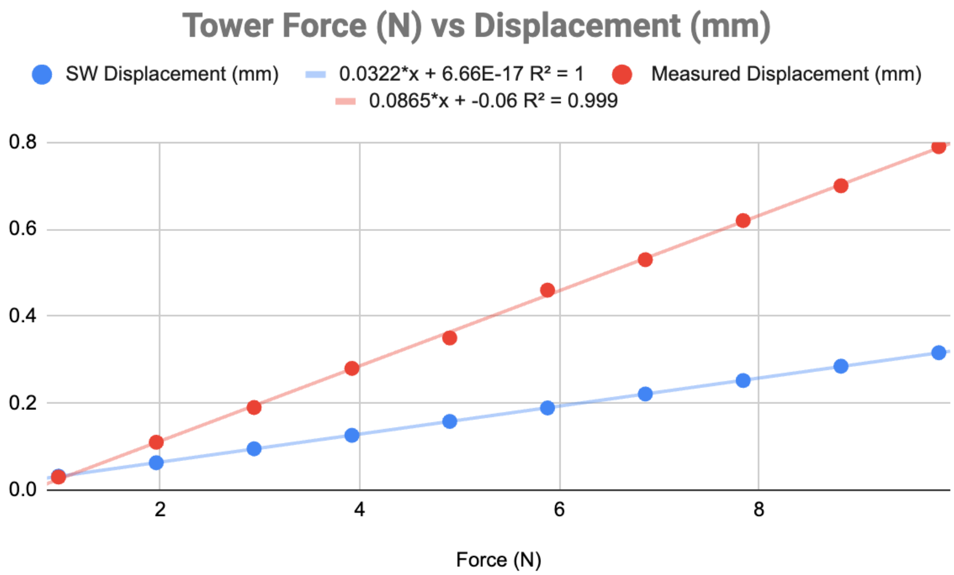


Figure 12

Plotted deflection data with respective line-of-best-fit equations and R^2 values

2.5 Tower Volume

The total volume of the tower assembly (excluding the rotor and motor) is **16.96 in^3.**

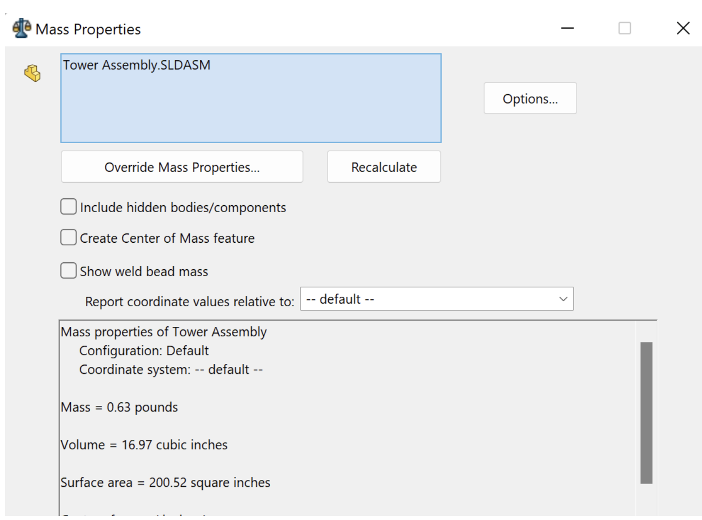


Figure 13

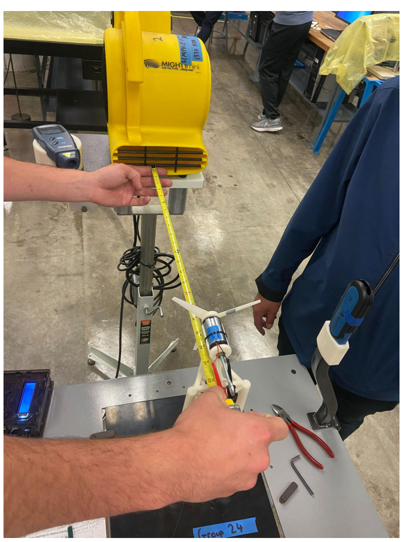
Solidworks Mass Properties window for tower assembly

3. Testing and Results

3.1 Method

Testing was a two part process consisting of a power output test and a deflection test. So as not to negatively affect the power test should any damage befall the tower, the deflection test was done second.

The power test consisted of an air blower pointed at the tower, around 17 inches away, blowing at ~25mph. This was measured with an anemometer on a stand in front of the rotor, and a tape measure. The tower was fixed to the table using clips and the motor was held in its basket using a plastic zip tie. The motor was connected to a data logging box using two quick-disconnect clips and had the rotor mounted on the front. The data logging box outputted voltage, amperage, power, and resistance. It also had two potentiometers mounted on the front to adjust resistance in large and small increments to allow the peak output power of the rotor to be found. Mounted alongside the air blower was a tachometer to measure rotor RPM.



Figures 14 & 15

Air blower roughly 17 inches away from tower blowing air at ~25 mph & anemometer on stand

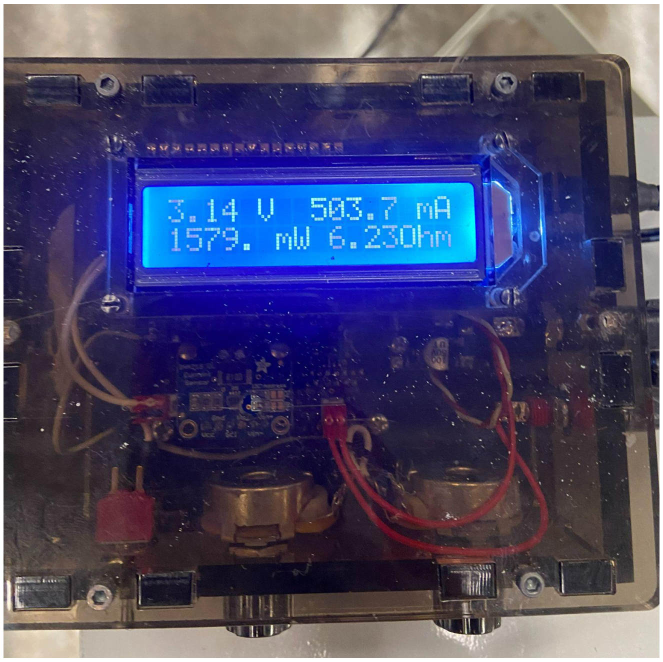


Figure 16

Logging box outputting voltage, amperage, power, and resistance

To start the power test, we first checked which direction the rotor performed better by turning the blower on, measuring the rpm, then flipping the rotor and trying again. We had opted to print our rotor upside down to make the support structures easier to print. Thus when we flipped our rotor such that the raised text was facing the motor, it performed substantially better (judging from the significantly increased rpm).

The next step was establishing the peak output power of our rotor by decreasing the data box resistance until the power displayed stopped going up. We mistakenly thought that ours was around 2 Watts which meant that when we divided by the number of data points we wanted to take, we ended up with increments that were too large for the eventual peak power that we reached of 1.7 Watts (i.e., we ended up with fewer data points than we initially would have liked).

Using those (incorrectly) calculated watt increments, we started back at the minimum power and recorded amps, volts, power, and RPM at increasing increments until we reached peak power. We then took a couple of data points past the peak power to ensure we had peaked and ended the test.

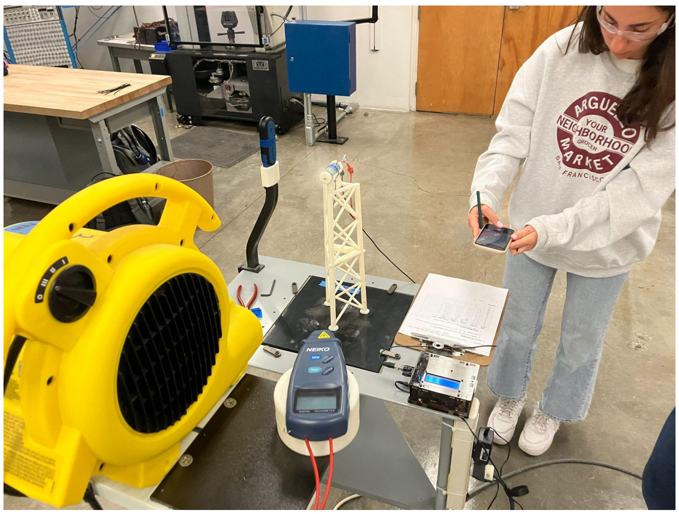


Figure 17

Alternate angle of the turbine in motion during data collection showing the tachometer

The displacement test was much more straightforward, with the tower mounted on a table using finger clamps, with an eye bolt connected to the motor basket upon which weights were added, and a plastic spacer sitting in the motor basket for a dial indicator to push against and show displacement. A string ran from the eyebolt, which passed over a pulley mounted at the same height as the tower, making adding weights easy. The dial indicator was mounted on a magnetic base and had adjustable arms, so making sure it was parallel with the direction of deflection of the tower was very easy. This step is crucial so as not to record non-axial deflection.

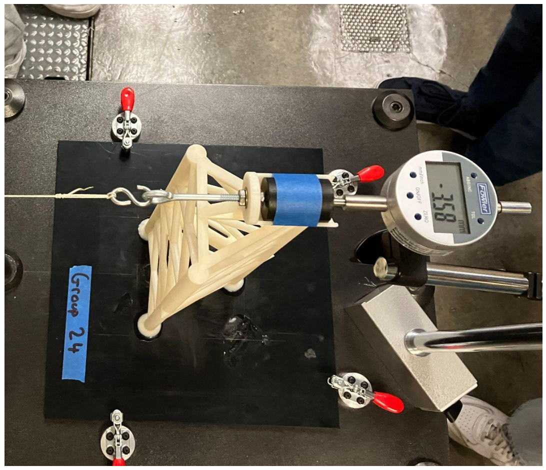


Figure 18

Top view of the finger clamps, plastic spacer, and dial indicator

After everything was set up, we added mass to the string in 100g increments until 1000g while recording the displacement on the dial indicator. Out of interest, we also went up to 5000g to see how displacement changed past the yield point of the tower.

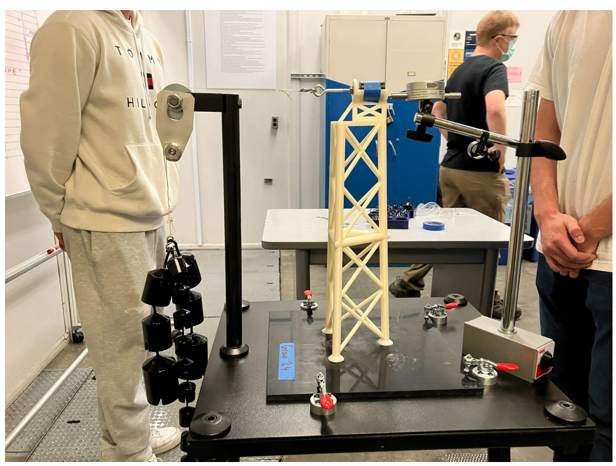


Figure 19

Side view of the added masses, pulley and the tower

3.2 Stiffness and Power data

Load (Kg)	Force (N)	Deflection (mm)	Stiffness (N/m)
0.1	0.98	0.03	32667
0.2	1.96	0.11	17818
0.3	2.94	0.19	15474
0.4	3.92	0.28	14000
0.5	4.9	0.35	14000
0.6	5.88	0.46	12783
0.7	6.86	0.53	12943
0.8	7.84	0.62	12645
0.9	8.82	0.7	12600
1.0	9.8	0.79	12405
1.5	14.7	1.24	11855
2.0	19.6	1.67	11737
2.5	24.5	2.08	11779
3.0	29.4	2.44	12049
4.0	39.2	2.81	13950
5.0	49	3.74	13102

Figure 20

Table showing deflection depending on the load on the tower

Voltage (V)	Current (A)	Power (W)	Blade Speed (RPM)
5.32	0.0927	0.489	7900
5.19	0.12	0.621	7700
5.12	0.141	0.735	7670
4.93	0.169	0.84	7550
4.80	0.201	0.96	7430
4.78	0.223	1.061	7330
4.68	0.25	1.18	7260
4.47	0.29	1.29	7050
4.30	0.327	1.42	6900
4.00	0.385	1.58	6600
3.60	0.46	1.7	6060
3.30	0.507	1.68	5700
3.15	0.513	1.6	5400
3.07	0.505	1.59	5380

Figure 21

Table showing power-related data

3.3 Results

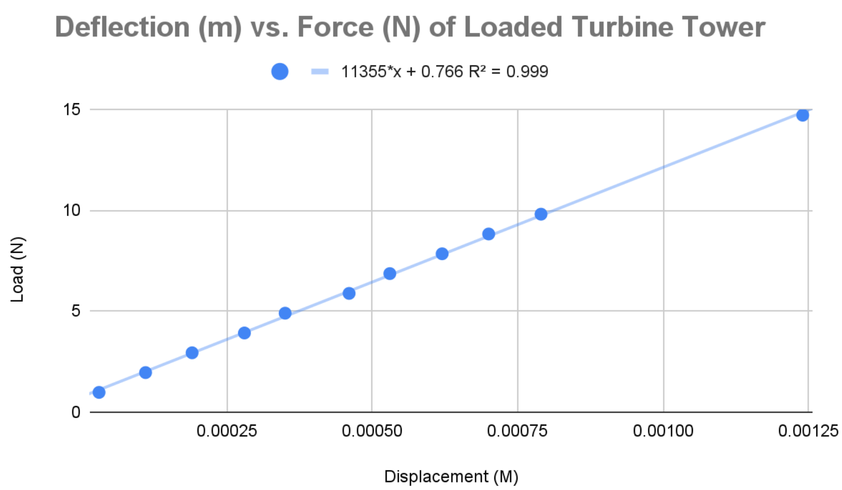


Figure 22

Graph showing load vs displacement

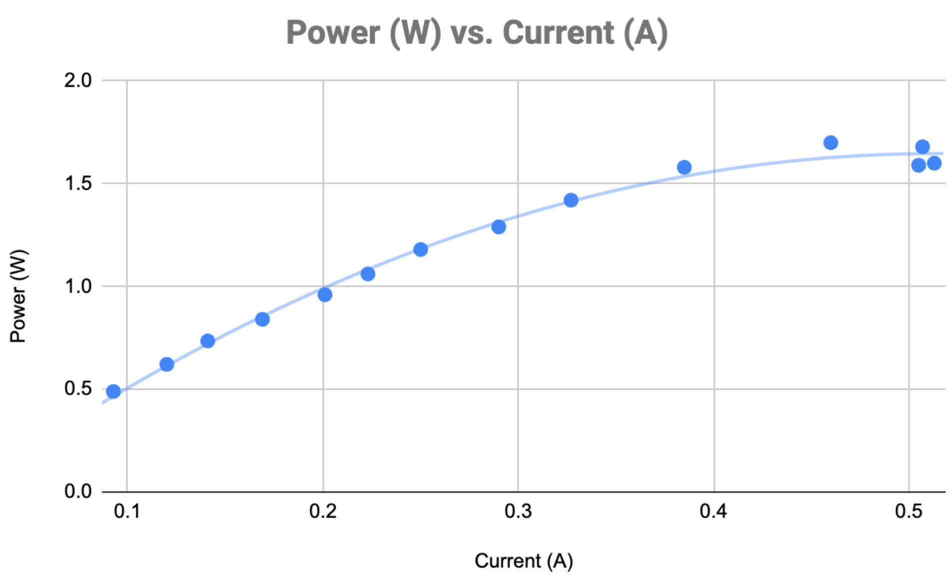


Figure 23

Graph showing current vs power

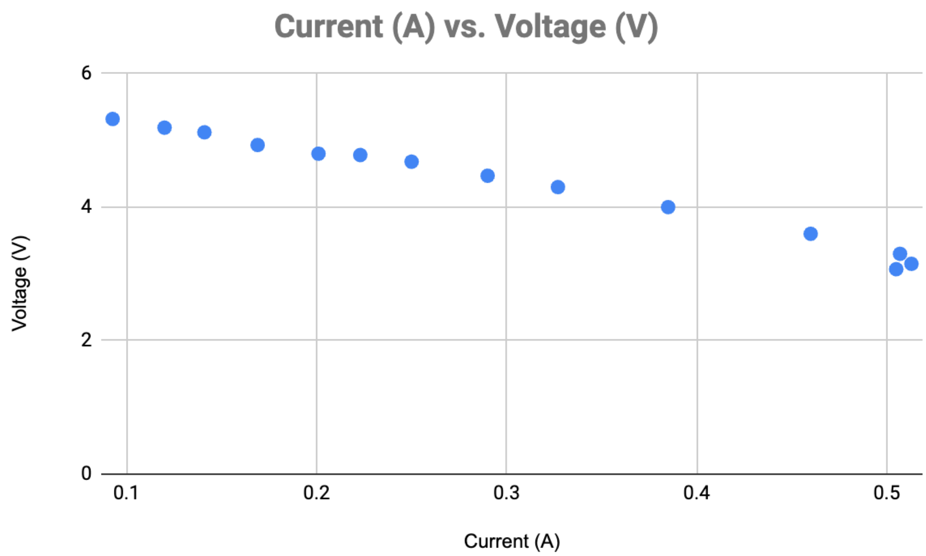


Figure 24

Graph showing voltage vs current

Once the testing was complete and all the data compiled, we set out to determine how successful our design truly was by testing our tower's power output efficiency using the equation $P_{wind} = \frac{1}{2}\rho A v^3$. This equation describes the power generated by the wind (P_{wind}) as a function of the air density (ρ), swept area (A), and the wind velocity (v) involved in the given scenario. In our particular case, we are assuming the air density to be 1.204 kg/m^3 as that is the typical density for air at room temperature. Our blades ended up being the entire 3 inches allowed giving us a swept area of 9π in^2, which is roughly 0.018241462 m^2. As mentioned earlier, our wind speed was about 25 mph or 11.176 m/s. This would provide us with a theoretical power output of 15.3290525627 Watts. In calculating the actual efficiency of our tower, we used the typical efficiency formula of efficiency = $\frac{Pgenerated}{Ptheoretical}$x 100%. Ultimately, our tower had a total efficiency of 11.09%.

4. CAD Drawings

4.1 & 4.2 3D Assembly Drawing & Exploded View of Wind Turbine

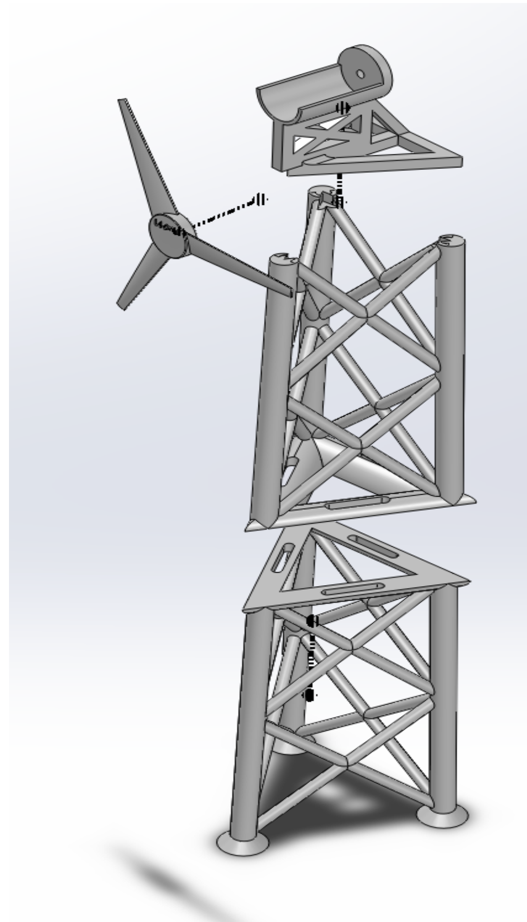


Figure 25 & 26

3D assembly view of the wind turbine & 3D exploded view of the wind turbine

4.3 2D Drawing of the Tower

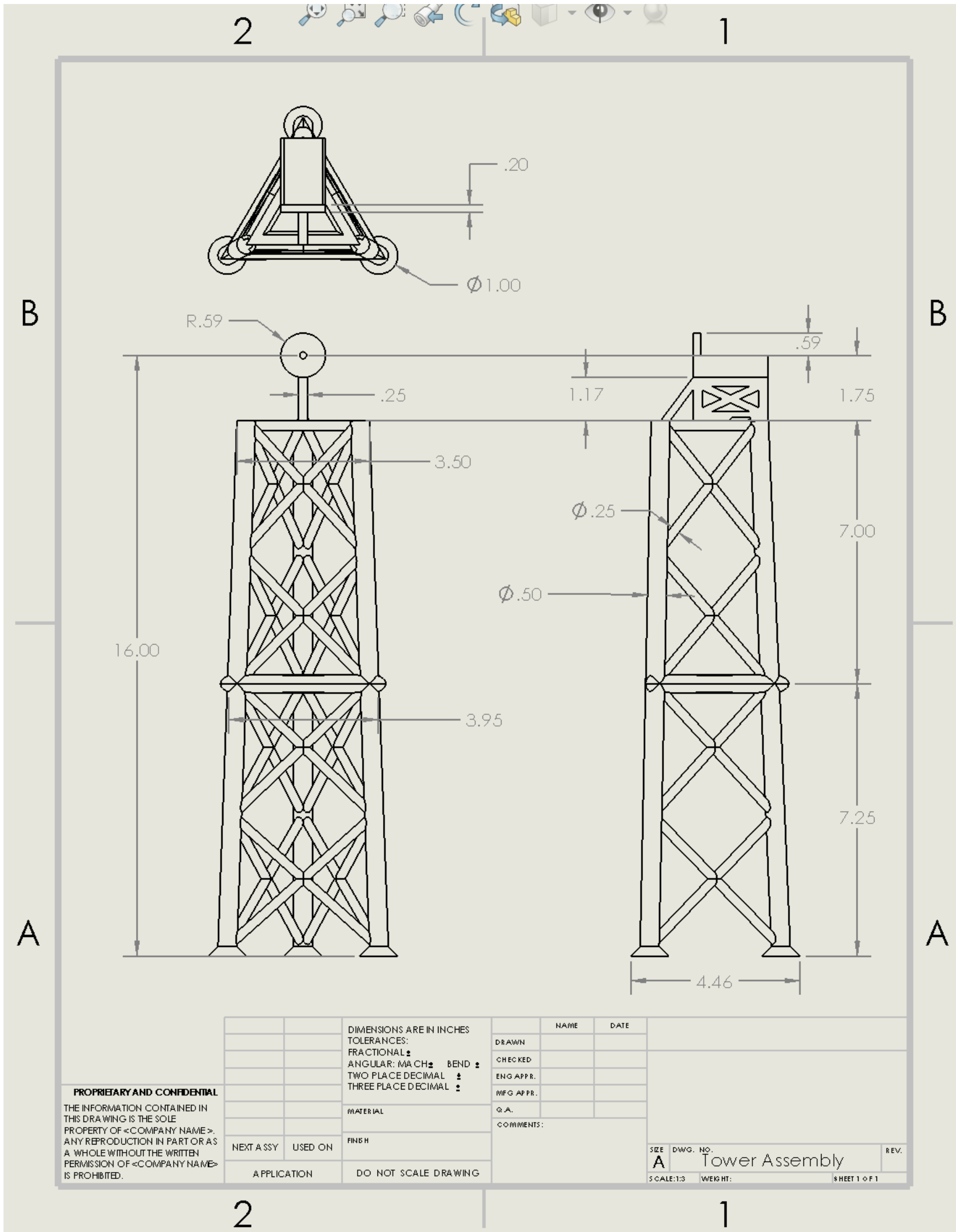


Figure 27

2D drawing of the tower assembly with overall dimensions (see appendices for original drawing)

5. Conclusions

5.1 Summary of Work

Overall, this project aimed to design and test a 3D printed wind turbine. We prioritized stability when designing the tower, opting for a lattice structure to provide strength while still minimizing the volume and material used. We conducted research on the aspects of good turbine blades, and designed various tower concepts before finalizing a tower and blade design. Then we drew the 3D model in Solidworks within the design constraints we were given. The final design had three blades and met all design restrictions and requirements.To ensure that the turbine would function as we intended, we optimized the model using Finite Element Analysis and conducted multiple stress tests. After the design was complete, the model was printed, pieced together, and tested. During the final tests, our tower featured a stiffness of 11571N/m and generated around 1.7 watts at the maximum.

5.2 What Was Learned

The project was enjoyable and engaging, providing us with practical knowledge in the application of Solidworks to real-world scenarios. We discovered the extensive potential and practicality of this software by creating a physical model of a wind turbine. From the initial stages, where each team member created an individual turbine design, we learned that communication and compromising was crucial in a team setting. Sharing our thoughts on how and why we designed our turbines the way we did was a productive experience, and we learned from each others' research before collectively deciding on the best parts of each design to incorporate in the final version. Moreover, this project allowed us to gain insights into each team member's communication style and strengths, which we leveraged to divide the work effectively.

For example, some group members were more experienced with Excel and plotting graphs, while others were better at data analysis, so we divided tasks accordingly. Some valuable takeaways from this project include the importance of effective communication, patience, doing prior research, and seeking clarification when needed.

5.3 Outcomes

The E26 Final Project required the group to apply the design skills we learned in class and in the lab to design, build, and test a wind turbine. In addition to using Solidworks design skills, we were required to be creative, work as a team, and communicate effectively.

The final design had three blades and met all design restrictions and requirements. The tower was capable of handling a load of 5 kg and had an overall stiffness of 11571N/m. The turbine generated a maximum power of 1700 mW when the rotor recorded a blade speed of 6060 rpm. The overall efficiency of the turbine was 11.09%, which we calculated using the power generated by the wind (P_{wind}) as a function of the air density (ρ), swept area (A), and the wind velocity (v). The project was overall successful, with no significant roadblocks or failures encountered throughout. These results explain how we achieved better results than most groups.

Results aside, this project allowed the group to learn more about different Solidworks tools, hands-on manufacturing, and iterative design. While designing the turbine, we learned how to use FEA and modify the design to make improvements. While constructing the turbine, we gained manufacturing experience with gluing the parts together and ensuring a strong, secure fit. While testing the turbine, we learned how to analyze a physical model and interpret the results of the test. As a whole, the final project was an invaluable learning experience for everyone.

6. Recommendations for Future Work

The weaknesses and limitations of the tests conducted on the final design reveal three areas that could be reiterated.

Firstly, the limitation of height on parts of the design due to the size of the 3D printer introduced a potential point of weakness in the glued joints of the final tower assembly. In order to address this in the future, we could print the entire structure at once or even injection mold it.

Additionally, the settings used for 3D printing the final product could be modified to increase the strength and accuracy of the design. For instance, printing with a polycarbonate filament or increasing the infill density would improve the tower strength with no modification to the 3D model.

Assuming the same constraints on the design, future iterations of the structure could involve collecting quantitative and qualitative data about each of the feature types of the turbine and conducting additional tests to achieve optimized efficiency, reliability, and stability. We could also investigate outside of the design constraints in order to extend the improvements with parts that require more attention, such as the connection point between the tower and the blades. For instance, replacing the motors or developing a new design pattern for the uppermost portions of the tower could improve our test results. In future iterations, we could explore different numbers of blades and modify the blade shape and twist to achieve a potentially better power output and decreased deflection.

7. References

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8. Appendices

Raw results data & trial graphs:

E26 Tower Testing Data

Tower and Rotor CAD files:

Tower Project CAD