Berkeley Breeze Final Report

The Design, Construction, and Testing of a Small Wind Turbine

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PROJECT SUMMARY

This project posed a comprehensive challenge; design, model, build, and test a 3D-printed wind turbine tower. We were tasked with designing a blade that could generate maximum power, as well as a support tower that was both rigid and lightweight. These criteria mirror some of the most critical challenges faced in the construction of commercial-grade wind generator turbines, an ever-more relevant concern in a world that is turning increasingly to alternative energy.

Our design process focused on aerodynamic aspects of the blade: the number of blades, the angle of the blade edges, airfoiling, and mass. For reasons described in the Theory and Design sections of this report, we finally settled on a relatively heavy five-blade design with a significant airfoil, giving the blade's cross-section a slope of 10 degrees on the front and 17.5 degrees on the back. For the tower, our final design prioritized rigidity and aimed secondarily for lightness: a hollow cylindrical tube that narrows as it ascends, with a broad base. For added rigidity at a minimal weight cost, we also included guylines made of an unspecified metal alloy, nuts and bolts, and 3D printed wire tensioners. Our design aimed for an efficient use of material, as well as clever design decisions, to maximize its desirable factors.

The testing process was composed of measuring power output with an electrical meter (current, voltage, and power data were recorded under various electrical loading conditions), measuring the rotations-per-minute using a meter and a reflective strip attached to the blade, weighing the tower using a scale, and testing the stiffness using weights, a pulley system, and a deflection dial-indicator. The collected power output data was plotted and a quadratic least squares polynomial was fitted to the data. The maximum power on this regression curve was 1.8545 watts, or 19.1% of the theoretical maximum efficiency for an ideal turbine blade with the same swept area. The tower and blade assembly cost $167.20 and with with attached guy wires totaled in at a mass of 1364 grams. A least squares linear regression of the load vs deflection data yielded that our tower achieved a stiffness of 29.768 N/mm. When divided by the towers total mas, this yields a stiffness to mass ratio of 21.842 N/mmKg.
Thus, our tower was very successful in rigidity, relatively successful in power output, and on the higher side in terms of mass. We satisfied the conditions of the project to the best of our technical ability, and as a cohesive team. We consciously made trade-offs in the weight category to make our tower very rigid, but we had no significant failures. In fact, we even had fun.

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INTRODUCTION

In this project we were tasked with creating an optimized wind turbine, from conception to assembly to assessment. Not only was this project relevant to the current political climate of our country– where alternative energy sources are increasingly being thrust into the spotlight– it was also relevant to all of us as aspiring mechanical engineers. This challenge pushed our team to delve into aspects of team-building, communication, design, Finite Element Analysis, manufacturing, and data analysis that are uniquely carried out in a team setting. Through pouring intensive work into every step of this project, we learned about such diverse topics as material properties, lab safety, creating our own tools, and knot-tying.

The challenge in building this wind turbine tower was in maximizing its relevant attributes to create a project that would perform well under the given testing procedure. Since a wind turbine is really only as valuable to society as its electrical power output, this was fittingly the first criterion. This is directly tied to how much wind a given blade is able to catch, how much energy is lost to air friction and generated turbulence, the mass of the blade itself, and other, lesser aerodynamic concerns. Since building any structure in today's capitalist economy is about striking an optimal balance between cost and benefit, material costs factor hugely into the analysis of a real wind turbine design. Thus, mass, or rather lightness, was the second criterion. Finally, since any tall and narrow structure stands the risk of deflecting in a heavy wind, during earthquakes or under other extreme conditions, rigidity is key. The importance of the rigidity of a tower is compounded by the fact that any amount of deflection redistributes the strain on a structure towards joints and other weaker points, thus increasing the deflection even more and potentially spiraling into a destructive cycle that can lead to collapse. While there are certainly other important concerns in the construction of a commercial and full-size wind turbine tower (such as aesthetics, noise pollution, and safety to birds and other wildlife), the three principles of power, lightness and rigidity are some of the most important. Additionally, they are relevant to the coursework of this class, and also scalable in order to be measured easily on our small wind turbine project.

There were also standardized technical specifications that our tower had to meet. Both the tower and blade would be 3D printed of ABS plastic, and our team was responsible for the cost. Including support material, the tower could be no more than 20 cubic inches of material, and had to be printed in 2 parts to accommodate the 3D printer size. The tower was to be 16 inches from base to the center of the generator (see fig. 1), which had to be housed in a supportive structure at the top. The swept area of the blade had to be no larger than 6 inches, and the blades were to be built out from a standardized hub for which we were given the CAD file. The whole project would be mounted on a given support platform made of ⅜ inch thick ABS. Guylines were permitted, and towers were to be designed to withstand wind coming from any direction, not just one.

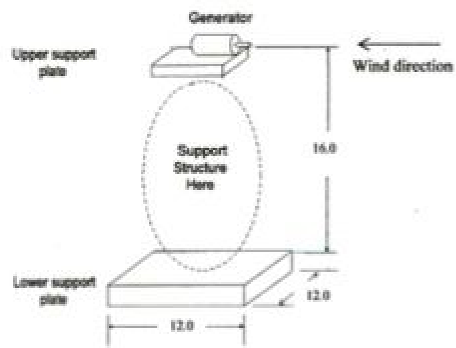


Figure 1: Some of the project specifications, illustrated

Another key component of this project was the team in which it was carried out; team-building skills were emphasized in this project through a series of assignments, surveys, and workshops. The end goal was to build teamwork skills that are invaluable to any practicing engineer in the workplace, as well as throughout school. We were asked to examine the diversity of our team-- skills, backgrounds, areas of interest, resources-- and make a plan to leverage those to the optimal success of our project. Additionally, we were surveyed throughout the duration of the project to produce quantitative and qualitative individual and team feedback. These opportunities for reflection were designed to give the team and its members a chance to change tactics if something was clearly not working.

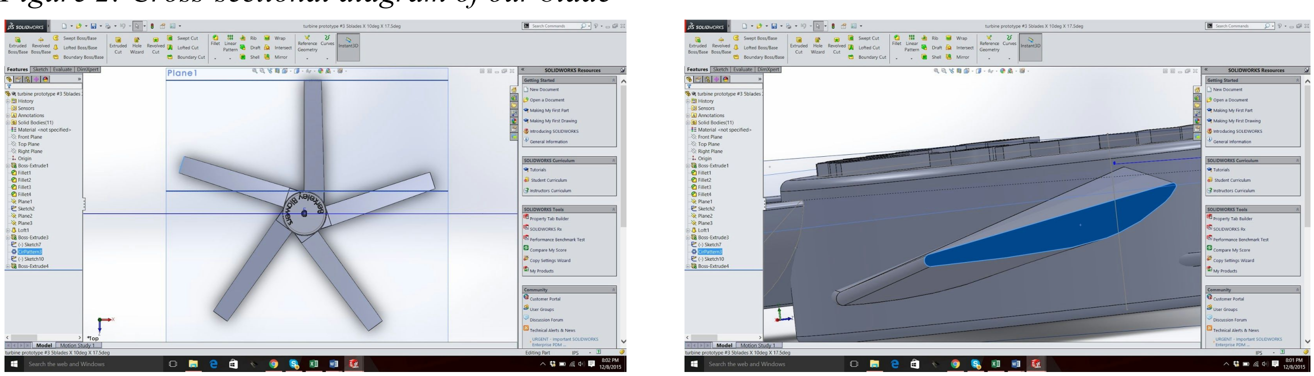
The convergence of these different aspects of the wind turbine assignment created an engrossing engineering project that challenged us to grow technically as well as intuitively.

In creating our specific tower as our personal answer to this prompt, our team looked to our diversity of skillsets to create effective and out-of-the-box solutions to the challenges of the project. When faced with a myriad of valid ideas and opinions, we turned to democratic principles of voting, persuasive discourse, and scientific testing to determine which idea had the most merit and would best serve our deliverable. When all else failed, our team was known to revert to the original, tried-and-true random decision generator: rock-paper-scissors. We also emphasized open and frequent group communication; we made Slack, the app and communication platform, into our home base (see Appendix B). Because it hosts CAD files as well as images and text, this proved to be an ideal way to group work. We also made extensive use of Google Drive, especially for writing this very report, as it allowed us all to co-work and edit the parts of the write-up with which we were most familiar. Finally, we made time for frequent in-person meetings. Even when not every member could attend, we found this face time to be invaluable in getting work done effectively and efficiently, not to mention for creating and testing prototypes in physical space. Taken together, these factors made for a very cohesive teamworking experience, in which we resolved our differences in productive ways and created a project we could all be proud of.

In order to make sure that our project met all the technical requirements, such as the correct height of the tower and swept area of the blade, we instituted an effective workflow in which no one person was in charge of the entirety of a part. Different teams of two or three tackled iterations of the blade and tower, and FEA was carried out by yet another person. In this way, we avoided mistakes and adhered successfully to the guidelines of the project.

Specifically, our blade focused on solving the challenges of catching the maximum amount of wind in the given 6 inch swept area, without creating inefficient wind eddies or turbulence, and slicing through the air with as little resistance as possible. We knew that an even number of blades would cause torque when one of the blades passed in front of the stem of the tower, disrupting its airflow and causing asymmetry. Thus, we had to select between a three-blade model or a five-blade model. We took our inspiration from desktop fans, which are similar in size to our wind turbine project and efficiently propel air using a five-blade model. Since the blades were so numerous, we had to make them thin to avoid creating unwanted wind eddies that would decrease our efficiency. In order to slice through the air while spinning, we opted for an aggressive 17.5 degree angle of attack, with a large airfoil (fig. 2).

Figure 2: Cross-sectional diagram of our blade



Our tower was simple in design: a hollow conical cylinder to effectively resist deformation. We focused on creating a balance between lightness and rigidity as elegantly as possible, widening the base of the tower based on Finite Element Analysis testing that showed this minimized deflection with a low material cost. The guy wires were also added along similar principles; for their lightness, their metallic properties could help our tower resist deflection where the material properties of ABS plastic and superglue failed. The images in the CAD Drawings portion of this report show in more detail the wireframe-style views of our tower model, demonstrating its hollowness and the way in which the top and bottom pieces join together for minimum deflection.

For this project, our team focused specifically on the graded criteria as well as pursuing elegant and unique solutions to the given challenges. We opted for a five-blade design and metal guy wires where other teams did not, and saw these design risks pay off on testing day. In addition, we chose to create a simple but efficient cylindrical tower that resisted deflection well. Within the specifications of this project, we found room to optimize and innovate our tower design to make it stand out and perform well.

THEORY

As stated above, the wind turbine tower was to be evaluated on three criteria: power output, weight, and resistance to deflection. We let these three principles guide our ideation, design and testing processes.

The theory behind the power generation capability of the blade was guided primarily by aerodynamic considerations. The design decisions we made, discussed in the "Design" section below, were geared towards reducing friction and unwanted turbulence around the blade while making the Bernoullli principle act in our favor. In addition, we were less concerned with efficiency for the blade as we were with total power output, since the weight of the blade is small in comparison to the weight of the tower itself. Therefore, we opted to use a five-blade design to catch as much wind as possible, even though the commercial popularity of three-blade wind turbines suggests that they make more efficient use of material. While thinner blades create a more aerodynamic leading edge and allow more room for airfoiling and inclination of the blades, we also wanted to be sure that our blades were thick enough to both resist deflection in the face of 25mph wind and 3D print cleanly.

For the tower itself, we aimed to achieve a balance between the conflicting goals of lightness and rigidity. In retrospect, we prioritized rigidity more heavily. We used the FEA simulation tools within SolidWorks to create a tower shape that minimized deflection and points of high stress while adding additional material at joints where we expected nonideal behavior, such as the junction between the two parts of the tower and the junction between the tower base and the base plate. Geometrically, we also knew that a cylindrical shape was the most effective at resisting wind coming from all directions, as stated in the assignment. This is because a cylinder distributes the stress evenly due to its radial symmetry, and thus avoids the points of weakness that corners can cause.

Once we learned that metal guy wires were allowed as part of the design, including them was a clear choice. For their relatively small weight, they can resist deflection and stress better than plastic, and they can reach all the way to the corners of the build plate to create a more effective resistance to tower deflection. The reasons for this lie in trigonometry, as shown in the diagram below:

However, we knew that there would be many challenges associated with the proper implementation of guy wires. For example, we would need to modify the base and our tower to create attachment points, and we would also have to devise a system for tensioning all four wires symmetrically. In the Design and Build sections, the intricacies of these challenges, and our solutions to them, are addressed.

DESIGN

Our design procedure occurred in three temporal stages, which corresponded to the three components of our tower; first we created our blade, then our tower, and then our guy lines.

The largest challenge in creating the blade was resisting the archetype we saw our classmates leaning toward: a light, three-blade design inspired by commercial wind generators. We realized that these large-scale turbines were much more influenced by material conservation than our smaller, cheaper turbines had to be. In fact, while a three-blade design makes more *efficient* use of material, it does not catch a maximum amount of wind that travels through its swept area. Thus, we decided that the weight of the blade was small in comparison to the weight of the tower, so we would pursue overall power generation capability over lightness of the blade. Te team also ruled out using an even number of blades due to concerns of the efficiency and structural stability of the blade. In a symmetric design when one of the blades passes into the "dead zone" area right in front of the tower body, the force acting on the blade in the dead zone decreases, no longer balancing out the force of the blade it is paired with. This unequal distribution of force causes a wobble to be introduced into the blade would cause a periodic wobble in the plane of rotation of the blade, leading to a decrease in performance and possibly build amplitude large enough to damage the blade.Due to these considerations, a five-blade design was what we settled on. Since the blades were so numerous, we decided to make them narrow and tapered at the tips to avoid causing turbulence that could actually decrease our power output despite catching more wind. Tapered blades are also more structurally sound, because they decrease the joint stress felt at the junction of the blades to the hub. Based on the Bernoulli principle and inspired by airplane wings, we decided that our blades should have both an aggressive angle of attack and airfoils (thicker at the trailing end and thinner at the cutting edge) to make maximum use of aerodynamic properties. This would help minimize air friction that could slow the blade down. With these agreed-upon principles in place, we set about creating a competition. Different members of our group differed on their opinions about whether the blades should be linear and flat, or curved like the blades of a pinwheel. We also did not know what the ideal angle of attack would be. We each created different CAD files of the blades that we thought were ideal. We then sliced and 3D printed them (fig. 3), and tested them in front of the wind of a desk fan (fig. 4). One of the most important lessons we learned from this experiment was that all of our blade ideas needed to be thicker if they were to print cleanly, especially at the thin cutting edge. The differences in the rotation speeds of the prototype blades under wind conditions were clear enough that we could decide a winner with the naked eye.

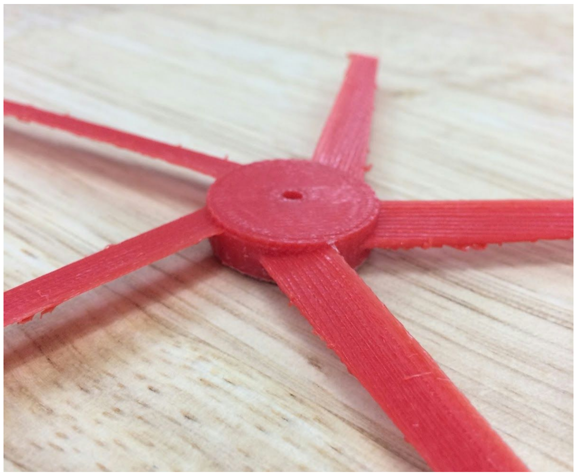


Figure 3: 3D printed flat blade prototype

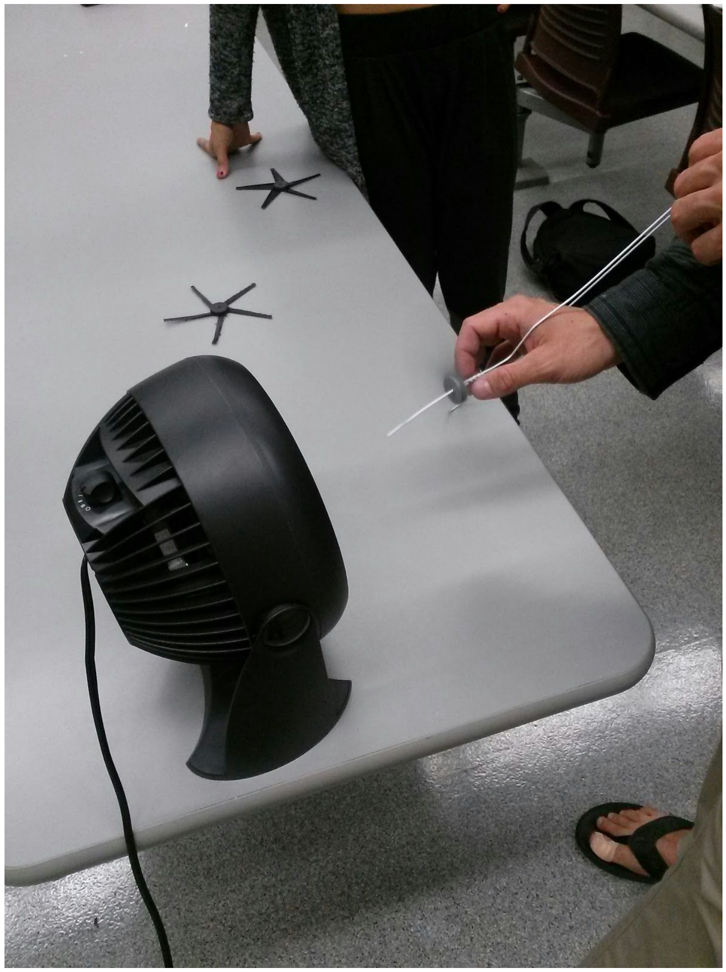


Figure 4: Testing of blade prototypes in front of a desk fan, with a coat-hanger as an axle

A flat blade seemed to be ideal, with an aggressive angle of attack that became less severe at the tips of the blades. This makes sense theoretically, because the tips of the blades are travelling through the air faster than the parts of the blade that are near the axis of rotation. We attempted to run a fluid flow simulation in solidworks to optimize and perfect our blade, but the simulation software on the school computers was not sophisticated enough to model this. The model did not allow for the rotation of the blade around the axis, leading to useless results (fig. 5).

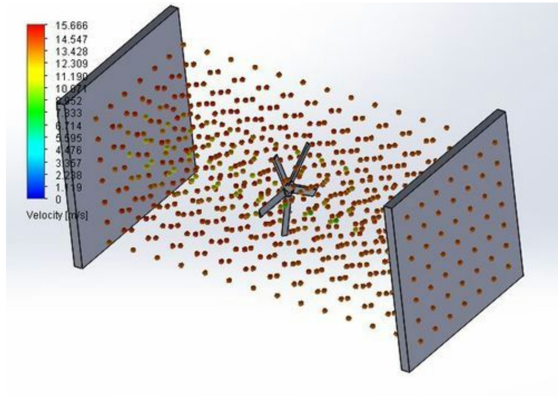


Figure 5: Solidworks fluid simulation testing of blade

Our tower also went through several iterations and Finite Element Analysis to arrive at its final state. Our original designs prioritized lightness highly, and so we were determined to use a truss, or lattice structure of bars for at least part of our design. Since triangles are the most rigid linear shape, we based our lattice structure on a regular pattern of of triangular shapes. However, we wanted to minimize and distribute the joint stress that would be felt at the junction of the tower and the baseplate, so we opted for a stronger, hollow-cylinder shape for the bottom half of the tower. The resultant tower looked like this:

Figure 6: CAD file (left) and 3D printed squished prototype (right) of our half-truss tower idea

However, through a combination of Solidworks stress-testing and common sense, we realized this design was far from ideal. There were unnecessary weak points, and the strength was not equally distributed throughout the tower. Additionally, modern commercial towers are leaning more towards a tubular shape over a truss or hybrid structure (Gwon). We went back to the drawing board.

Our second and final iteration was based on a circular cross section, used to ensure that it was was symmetric enough to be able to withstand wind from all directions. It tapered linearly in diameter as the height increased, because the applied bending moment during stress testing would be larger at the base of the tower than near the top. Thus, a larger diameter is needed at the base of the tower while a larger diameter at the top adds little to the tower stiffness and does not justify the added weight. This tower included no lattice component, because the lightness that a truss offered was just not worth the disproportionate decrease in rigidity.

In order to fully optimize our structure, it needed to be designed in order to be as stiff as possible per unit of mass of ABS. In order to achieve some insight into how to increase the stiffness of the tower the Euler-Bernoulli equation can be applied. For a loaded member the Euler-Bernoulli equation can be written as $v''''(y) = \frac{-w(y)}{EI}$ where v(y) is the deflection of the member at height y, w(y) is the applied load at a height of y is the applied bending moment on the member at a height of y, E is modulus of elasticity and I is the moment of inertia of cross section. The applied loading at each height is going to be set by the loading conditions and the modulus of elasticity is set by the requirement that the tower be 3d printed from ABS. The only parameter left to optimize is the moment of inertia of the cross section. With the cross section shape set as a circle due to considerations of symmetry, the moment of inertia is increased by increasing the diameter and hollowing out the cross section. By increasing the diameter of the cross section we increase the radius of gyration and by hollowing out the tower cross section, we can increase the moment of inertia while keeping the same mass of ABS. By doing this in our design we are maximizing the amount of stiffness that each unit of mass will provide and are making the design more effective and efficient. Hollow body to increase moment of inertia while minimizing mass (Youssefi)

Although the theoretical analysis is helpful in providing a conceptual framework for the design, a more realistic model is needed in order to get accurate results. In order to get these results we turned to Solidworks built in modelling and performed thorough Finite Element Analysis on this tower, setting the base as immobile and applying a 20 Newton force to the generator capsule, just as in the real test. We determined that the major point of stress was the junction between the top and bottom part of the tower, and that the deflection was greater than we would like (fig. 7):

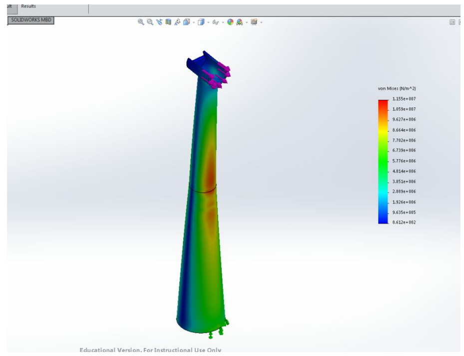


Figure 7: Stress Testing in Solidworks

Thus, we widened the base and added extra thickness in the area of most stress to combat these problems. Widening the base proved to be a worthy investment, because even when using the same amount of material a wider tower is more stable. The junction between the top and bottom pieces of the tower was designed with strength in mind; we first tried a series of peg-and-hole joiners that were feeble enough to just snap off after being 3D printed. Thus, we abandoned this idea and created instead a concentric-cylinder junction that added rigidity (and weight), and would provide more surface area for the glue to bond to (fig. 8). Finally, we inscribed our team name on the base of the tower for easy identification.

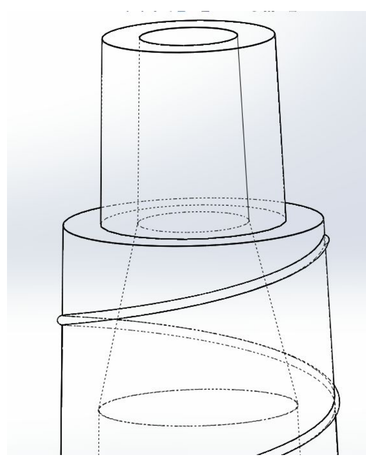


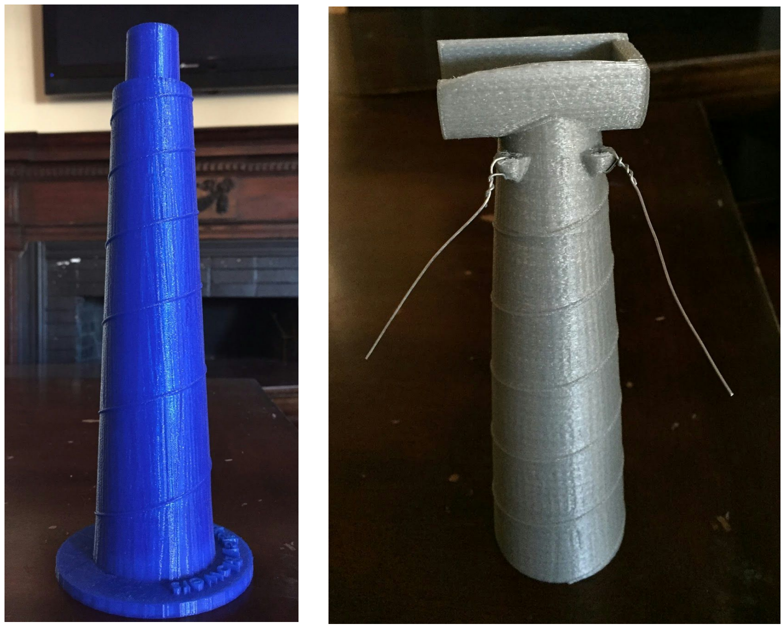
Figure 8: wireframe model of bottom part of concentric-cylinder junction

In developing the guy lines (discussed further in the subsequent section, Guy Line/ Tensioner Development), we knew that well-tensioned metal wires would add a boost in rigidity that no ABS plastic feature could. We first went to the hardware store and bought the second-thinnest metal wire they had (the thinnest wire could only withstand a force of 5lbs, and we did not want to risk snapping under the 20lb pressure that was to be applied during testing). The wire that we bought could withstand 10lbs of force, which, coupled with the strength of the tower and the fact that we planned to place 4 guy wires radially around the tower, seemed like a safe choice. The wire was made of galvanized steel, with a diameter of 0.73mm. Based on trigonometric principles outlined in the Theory section, the guy wires would prevent more deflection if we could place them as far away from the tower as possible, and attach them as high up the tower as possible. Thus, we planned to place them directly at the corners of the base plate, and we designed attachment points on the tower directly under the generator capsule. The generator capsule was a horizontal elliptical cylinder shape, so that the generator could slide in from the front. The top was removed, to allow an open top with room to flex to accommodate the generator and hold it in place firmly. The capsule was designed with no tolerance at all, such that the flexing motion of the ABS would be enough to hold the generator in place (although tape was eventually added during testing).

On our tower, you will also notice a helical pattern embossed. Rest assured, there is a very well-thought-out reasoning behind this: we thought our tower looked boring. We wanted our tower to be recognizable and unique to identify it easily in a sea of similarly-cylindrical towers. In commercial wind turbines, aesthetics are also important. A key concern of wind-farm development is the impact on the landscape visually, and we wanted our tower to look more than just purely utilitarian. Now, although we wanted to add aesthetic appeal, we didn't want to compromise structural integrity or print complexity. Thus we conducted a 3D printing prototyping test to see if the helix would require support material. Although Cura Software predicted that support would be required, when we ran the print without support on the type A printers in Jacobs, we found that support was indeed not necessary to achieve the helical pattern. On the higher-quality printers used to print our final design, some support was needed in the end.

Figure 9:

Prototype top and bottom to test thickness, diameter, connection, writing on base, helical pattern



Guy-Wire Tensioner Development

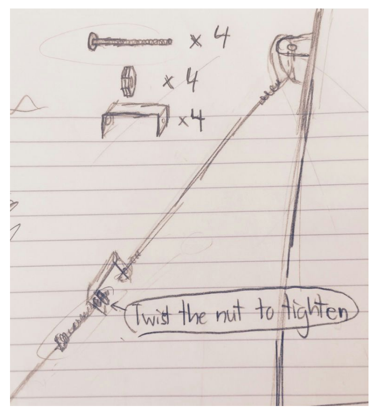
When we met with Professor Youssefi for our check-in, we made it clear that we were dedicated to the idea of guy wires. He suggested that we look into solutions to symmetrically provide tension to each cable once attached. We visited the ACE hardware store and learned about "turnbuckles"*(fig. 10)*. While these presented a possible solution to our problem, we were dissatisfied by the size and weight of the available turnbuckles. After extensive online research, we determined that our best option was to create our own "tensioner" based on our own specifications:

low

weight, attachable to wire on both ends, and relatively robust.

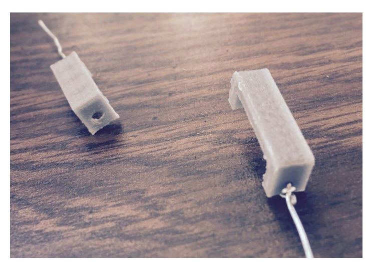
Fig. 10: turnbuckle

We began theorizing and sketching possible solutions. Our first idea consisted of soldering a screw to one end of wire and a nut to another end of wire. Once these wires would be fixed to the platform base and tower respectively, the motion of tightening the screw and nut would provide tension. However, we were quick to realize that this tightening motion would cause twisting in the wires, which was an unnecessary added burden. Our second idea was slightly more complicated. Two screws and two nuts would be needed per tensioner. Screws would be soldered to the ends of two different pieces of wire. Then, a middle piece would consist of bar stock with nuts attached to either end. To provide tension, the middle piece would have to be turned, leaving the wires untwisted. This second solution was too complicated (requiring right-handed and left-handed screws) and potentially too heavy. We also learned that soldering is not encouraged for mechanical applications, and that a better means of connection can be achieved with winding wire through holes and twisting it at the joints.



Our third idea was the winner (*fig. 11)*. Each guy wire setup would need one screw, a matching nut, and a middle piece of sheet metal or plastic that had appropriate holes. For the purpose of brevity, we named the middle piece the "tensioner". This solution was simple, light, and could provide the adequate tension in each guy-wire.

Fig. 11 : Sketch of Idea 3



With access to the Type A Machines in Jacobs Hall, we began the process of rapid prototyping the tensioner. Our first tensioner had three walls and a hole in each of the opposite walls that matched the size of the wire and the screw size we had in mind. After printing out the first tensioner *(fig. 12)*, we went ahead and purchased the screws and nuts.

Fig. 12: First prototype w/ wires

At this point, we went ahead and purchased screws and nuts. We searched for screws with small diameters and settled on 1 inch long #3 screws (Diameter: 7/64 inch). We chose flat head because we assumed that it would be easier to wrap wire around a flathead screw.

The figure on the right showcases Tensioner1 below our final two screw choices. The next figure shows the purchased screws fitted into Tensioner1. Immediately, we identified a design flaw in Tensioner1. There was not enough space for the nuts we purchased to fit onto the screw. Tensioner2, our next iteration, was very similar but had thicker walls and better fits for the screw and wire.

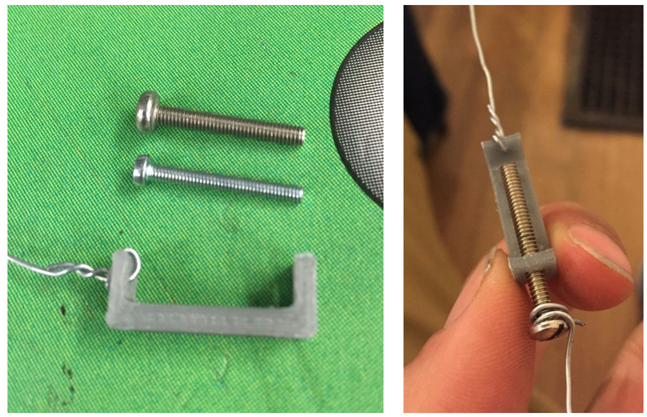


Fig. 13: Tensioner1 w/ final two screw choices

Tensioner3 (*fig. 14)* had a 4th wall for added strength because we were worried about the tensile strength of the thin Tensioners. However, Tensioner3 had a problem with dissymmetry. When the wire would be attached to the free end, it would need to wrap around one of the sides. To address this, we created Tensioner4. *(Fig. 15 Below: Tensioner4)*

Fig. 14: Tensioner3

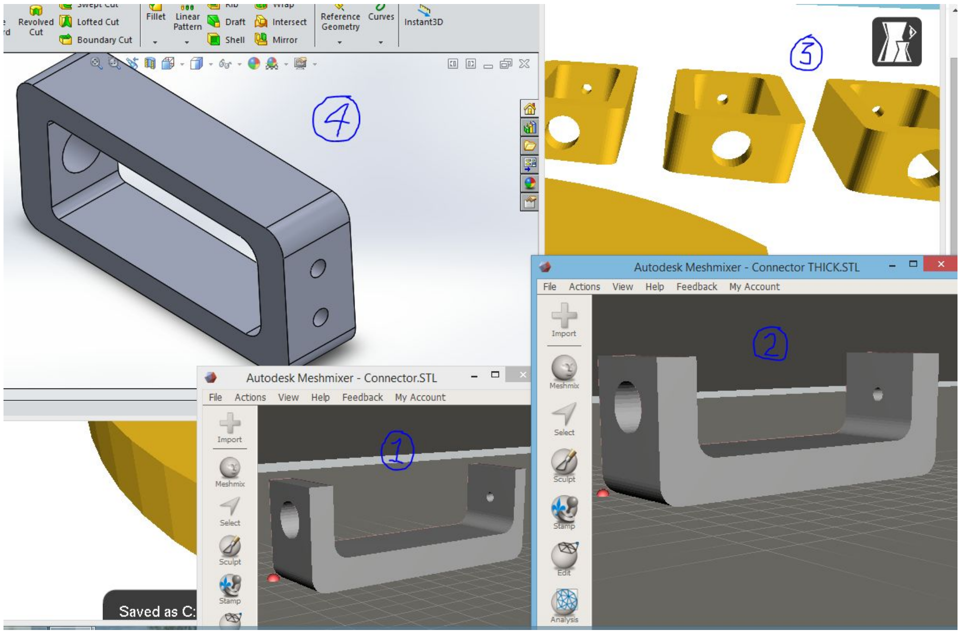


Figure 16: Screenshot of Solid Models of Tensioner1 through Tensioner4

Tensioner5 (*fig. 17)* had slanted walls to decrease the weight and make it easier to turn the nuts by hand. It later proved that it was still nearly impossible to hand tighten the nuts because the nut didn't protrude far enough outside of the walls. Tensioner5 also had a better wire connection port. By turning the orientation, we maintained the symmetry by reducing the number of holes back to one. However, it was more difficult to print because support material was required, and therefore post-processing such as sanding was a necessity.

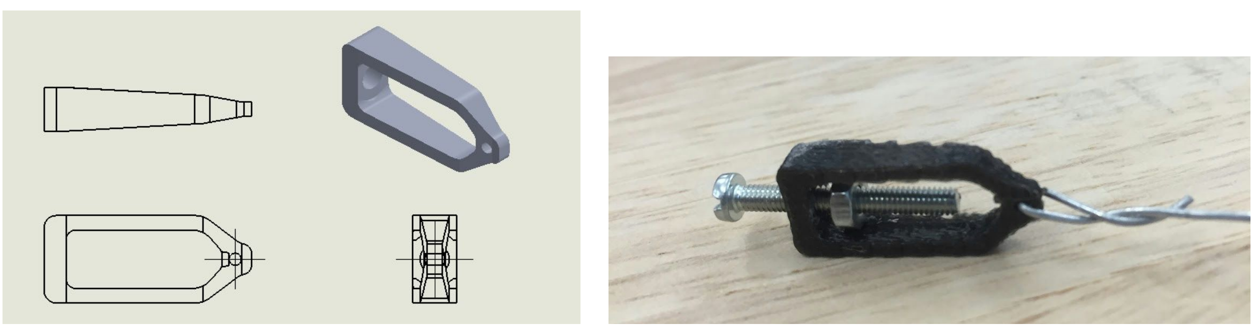


Figure 17: Tensioner5

Tensioner6 was a pretty significant redesign with intentions of robustness and usability. It was a last-ditch effort at creating a tensioner that was easy to physically tighten by hand or by wrench. By switching to a cylindrical shape (fig. 18) and reducing the width of the wall spanning the screw, it was to supposed to open up enough space for a finger to reach in and tighten the nut.

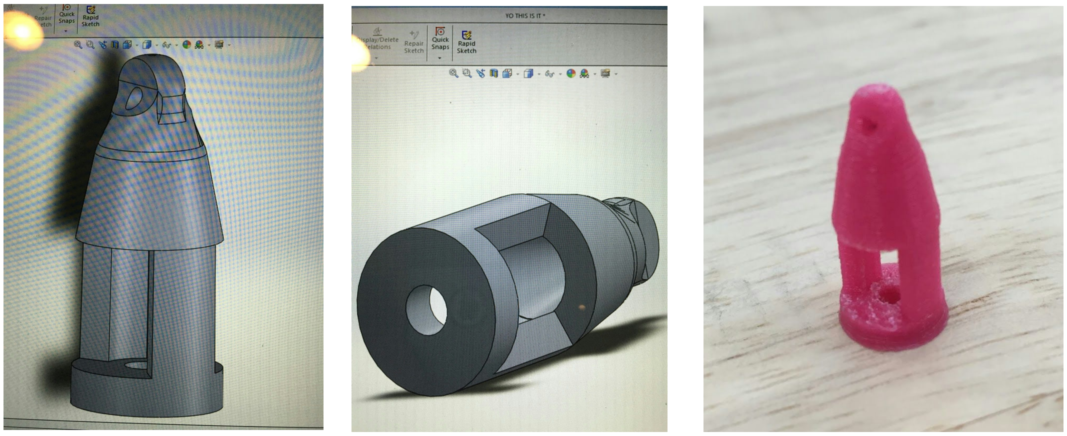
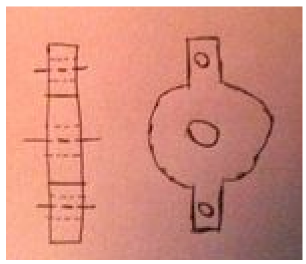


Figure 18: CAD models and 3D printed version of Tensioner6



Tensioner6 didn't solve the problem. While it was an elegant and robust solution, it didn't prevent the tightening process from being a nightmare. It was at this time that we had to take a step back and redesign with the intention of simple tightening. We turned to a simple solution *(fig. 19).* A simple extrusion with two holes for wire attachment sandwiching an attachment for the screw.

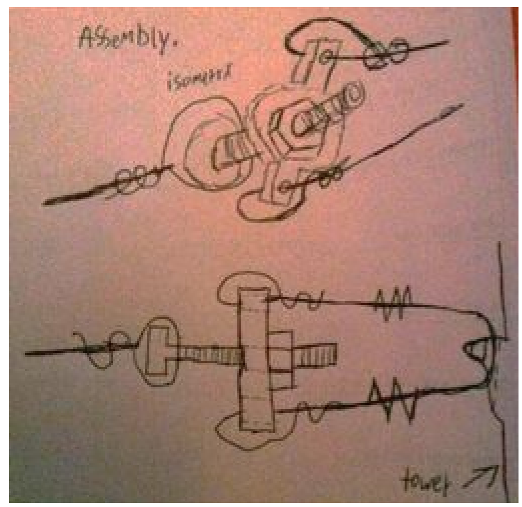


Figure 19: Sketches of Redesign

Tensioner7 *(fig. 20)* was very similar to our initial sketches, slightly more sophisticated than a simple extrusion with three holes. However, we knew that this tensioner would need to withstand a pretty serious shear force. While increasing the height of the tensioner would mitigate the risk, this would also put more stress on the wire because the connection would have to traverse a greater distance. Additionally, the sharp edges put unwanted pressure on the wires.

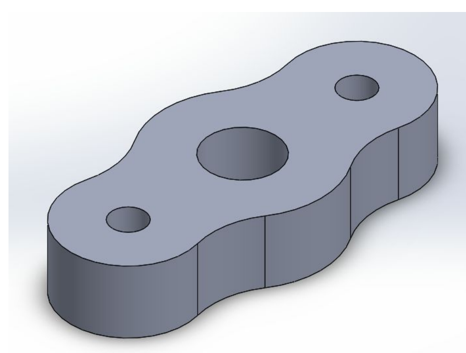
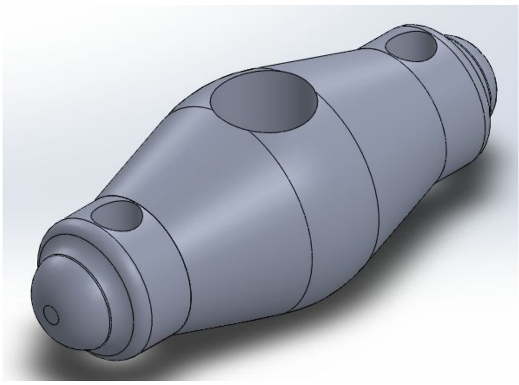


Figure 20: Tensioner7

Finally, we settled on Tensioner8 *(fig. 21)*. Tensioner8 had smoothed out edges to decrease the pressure on the wires and allow them to hug the contour as they wrapped around. It was designed to reduce shear and minimize the distance the wire must travel to get around the tensioner. It also had a flattened bottom to allow for the nut to smugly rest against its surface.



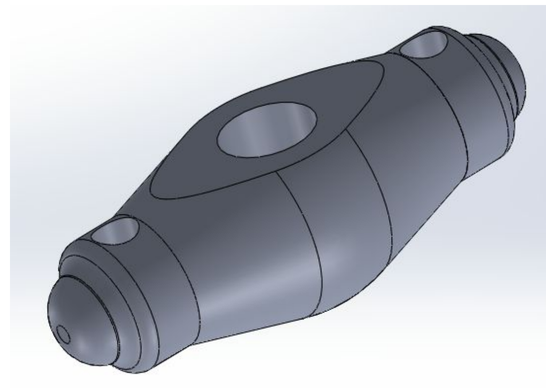


Figure 21: CAD models of final tensioner

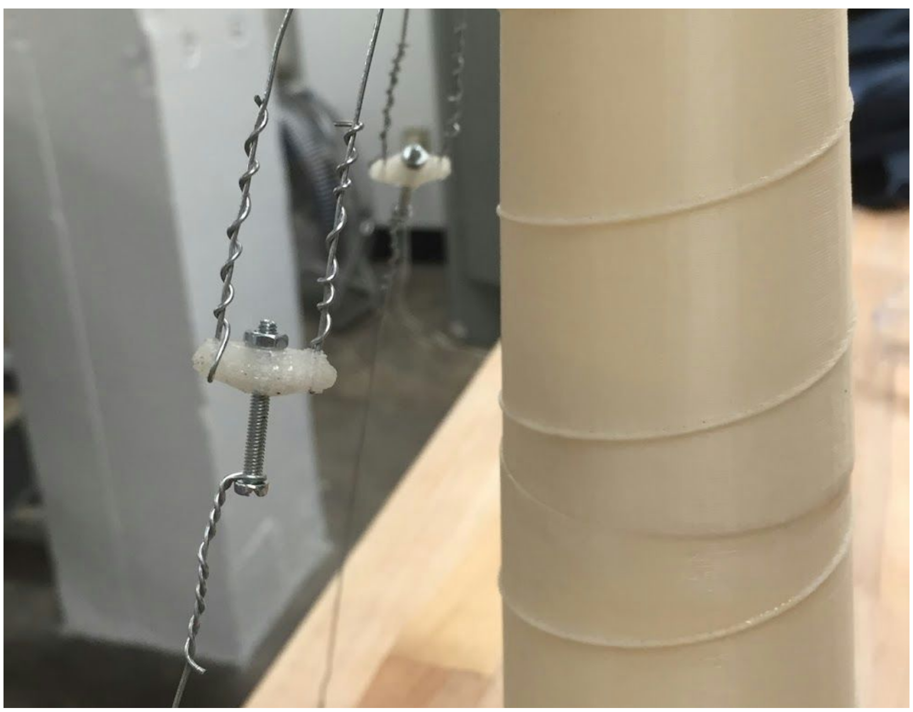


Fig. 22: Final Tensioner In Use (Printed out of Translucent PLA - only color that was available

Now that we had a tensioner that could be a tightened, we needed to make a tool to facilitate that actual tightening process. We couldn't find a small enough wrench in Jacobs Hall, so using a caliper to get precise measurements of our nut, we designed and printed a simple wrench. To ensure that all four guy wires had relatively similar tension forces, we plucked each wire carefully and listened to the tone, matching the frequencies (essentially tuning a guitar).

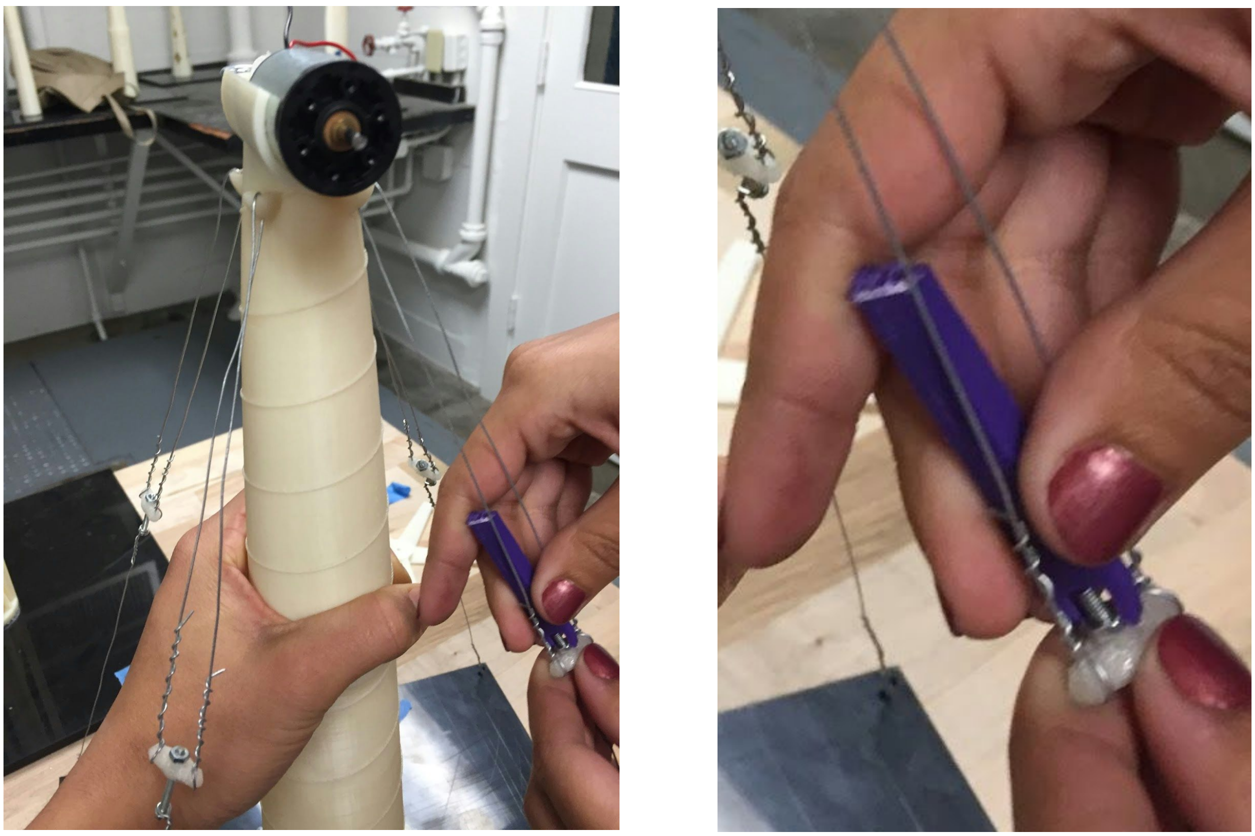


Figure 23: Tensioning one of the four guy wires with our 3D printed wrench

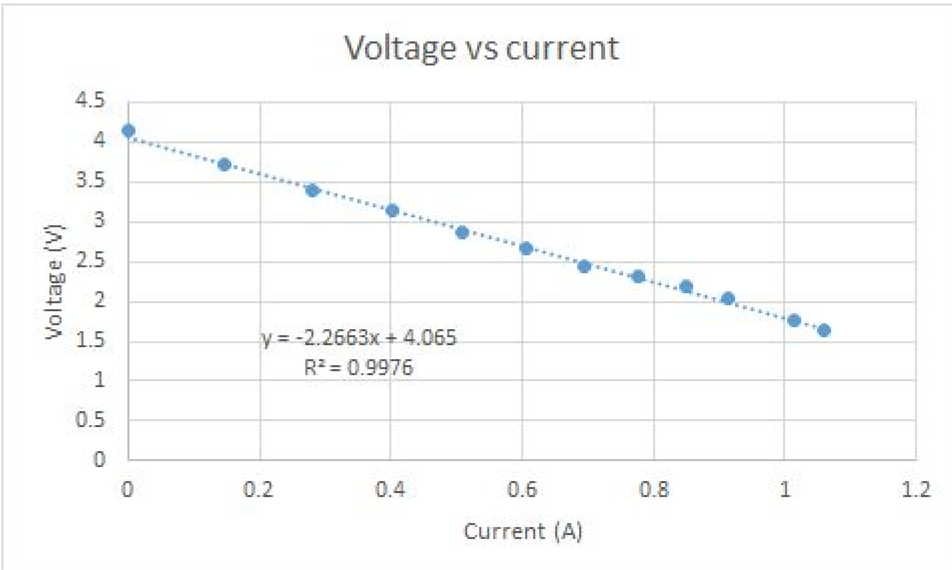
BUILD:

Both the blade and tower assemblies were designed CAD files in Solidworks. As such once the design was completed and enough modeling had been performed on it in order to validate the design, the CAD file was converted into an stl file and sent to 3D printing lab to be printed in 2 pieces. In order to minimize the amount of support material used during the 3D printing process, the top half of the tower was printed upside down so that support material would not have to be built up to the height of the entire part to support the motor mount and bottom half was printed upright so that the base would require no support material. Under this configuration the total cost of the tower and blade including the dissolvable support material was $167.20.

Once the part was finished printing we began the assembly process. With the help of the technician two small holes were drilled into the corners of the support plate upon which the tower rested. The guy line wire would later be fed through through these holes and twisted off at the end in order to anchor our guy lines to the support plate. Next the step was to glue the base of our tower to the support plate, glue together the two halves of the tower, attach the I bolt for stiffness testing to the motor mount, and wait for the glue to dry overnight. Once the glue was dry, the guy wire lines could be tied off to the tensioners and looped through the abutments on the top of the tower. The last step of the build process was then to insert the motor into the motor mount where if fit snuggly and place the blade on the generator. The generator was then pushed out so that the blade would be far enough away from the tower body that the guy lines would not interfere with the rotation of the blade.

TEST:

The first test of our wind turbine's performance was to measure the power that our turbine could generate. This was accomplished by securing the turbine to a stand using metal clips tightened by an allen wrench and connecting the generator output wires to a power meter which measured the voltage, current and power generation of the turbine. A reflective piece of tape was also placed on one of the wind turbine blades and an optical sensor was used in order to determine the rate of revolution of the wind turbine blade. After the tower was secured, blade was taken off of the motor and the high-powered leaf blower was turned on. The wind speed that the leaf blower produced was measured to be 25.3 mph before the testing began. During the testing the load drawn from the motor was steadily increased by flipping on small light bulbs in order to increase the resistance within the circuit. The raw data obtained is listed in Appendix A and the plots of the voltage vs. current and power produced vs. current are plotted below in fig. 18.



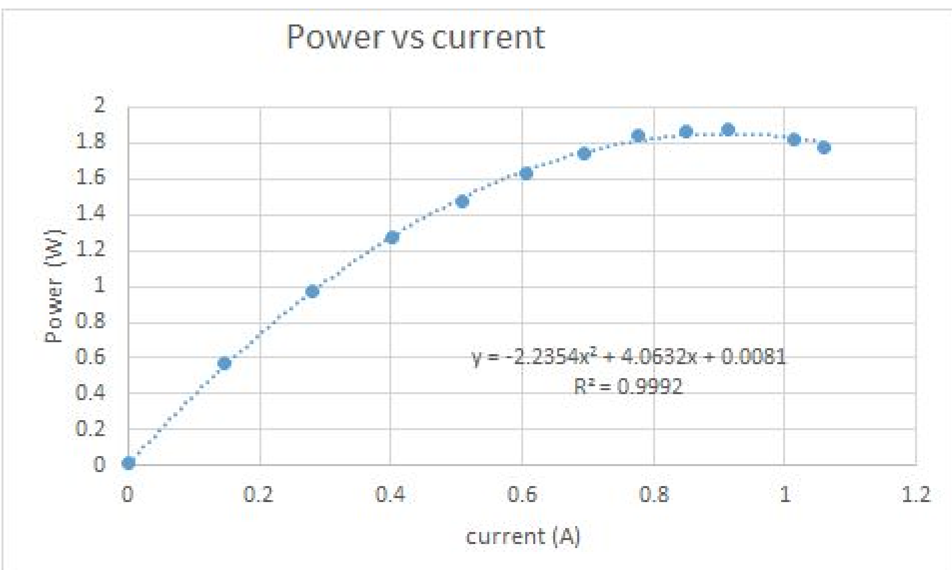


Figure 18: Graphical representations of our testing data

For the testing of the stiffness of the tower, the tower was secured to a table and a string was attached to the I bolt that was secured to the back of the motor mount of the tower. A blank cylinder was secured into the motor mount and zip tied onto the tower in order to provide a flat surface from which to measure the tower deflection. Weights were sequentially added to the the string in order to provide an increasing load from which to gain data points to determine the tower stiffness. During this process, care was taken to ensure that weights were never taken off of the tower as due to the hysteresis in the glue joining both halves of the tower and holding the support to the base plate which would cause a permanent deformation in the tower which would skew results. The raw data collected is given in Appendix A as well as in graphed in fig. 19 below.

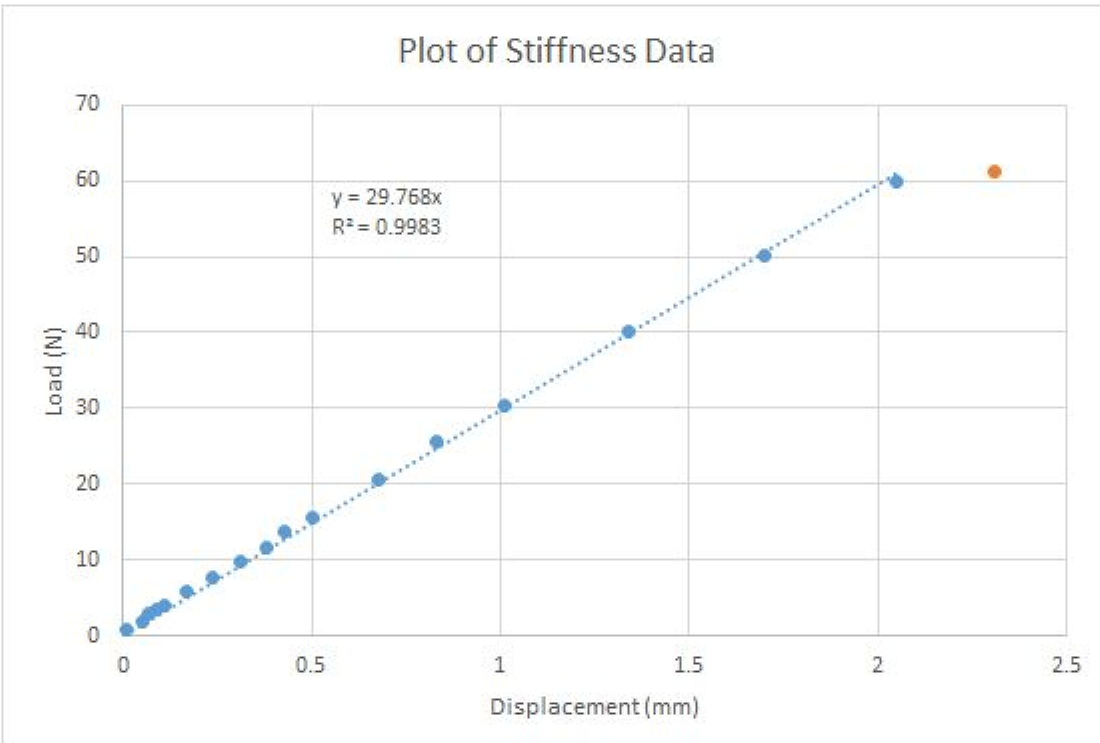


Figure 19: Load vs. Displacement

In order to calculate the efficiency of our wind turbine, we first calculate the maximum theoretical power that an ideal blade can produce, which is given under Betz' law as $\frac{16}{27} * \frac{1}{2} * \rho A v^3$. Plugging in the relevant numbers from our experiment yields a maximum power of

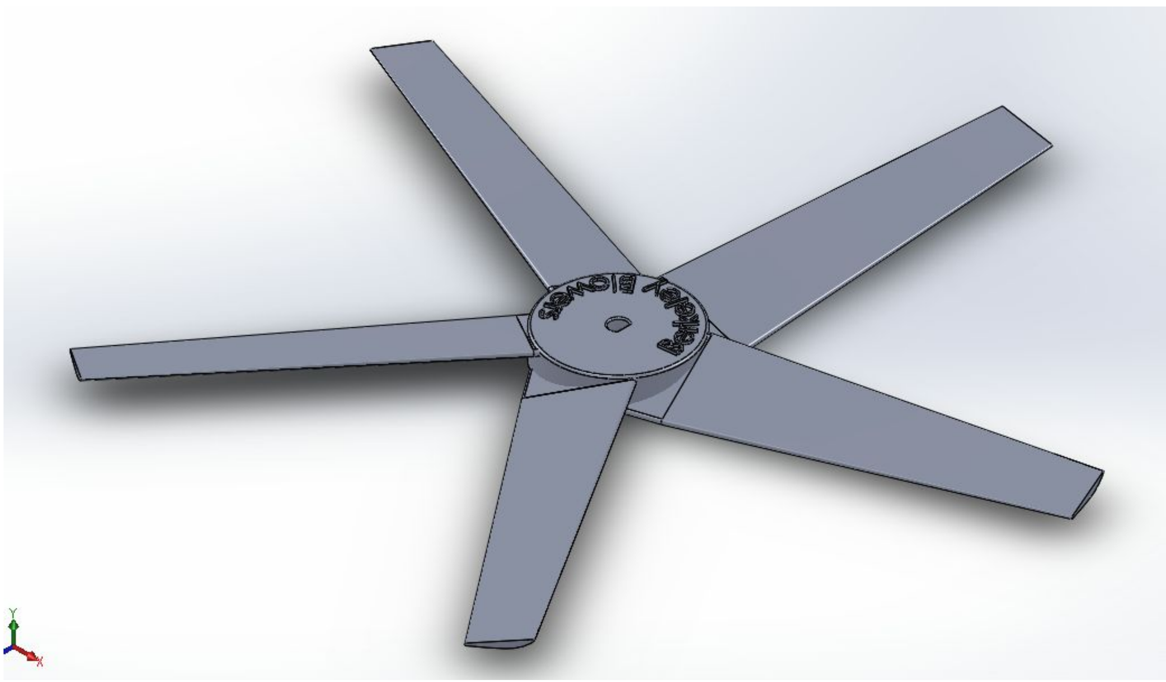
$\frac{16}{27} * \frac{1}{2} * 1.225 * .5 * \pi * (3 * 2.54/100)^2 * (25.3 * 0.44704)^3 = 9.579\ W$

In order to find the maximum power output of our turbine, we do not use the actual measured data, but instead a least squares regression through the data in order to remove any measuring errors. A second order polynomial was fitted to the data yielding the relationship between power in watts and current in amperes as: $power = -2.2354 current^2 + 4.0632 current + 0.0081$. Solving this equation for its maximum power output yields a maximum power of 1.8545 W. Dividing this by the maximum theoretical power generation for an ideal wind turbine of the same swept area subjected to the same wind speed of air and we obtain that the efficiency of our blade was 19.36%

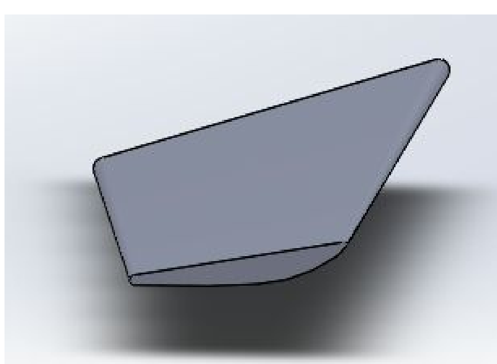
In a similar manner the load vs deflection data was fitted to a linear least squares regression line and the relationship obtained directly yields that the stiffness of our tower design is 29.768 Newtons per millimeter. The last data point measured (colored in orange in the fig. 19 plot of load vs displacement) deviates from the very strong linear trend of other data points significantly enough that it was removed from the regression. Dividing the stiffness of the tower by the towers mass of 1.364 Kilograms yields that the tower achieved a stiffness to mass ratio of 21.824 N/mmKg.

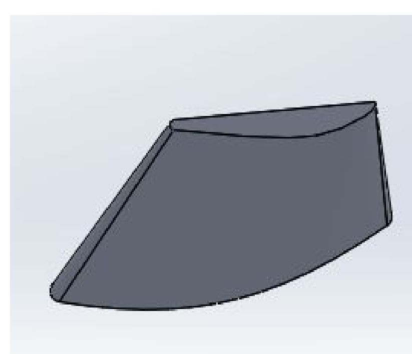
CAD DRAWINGS

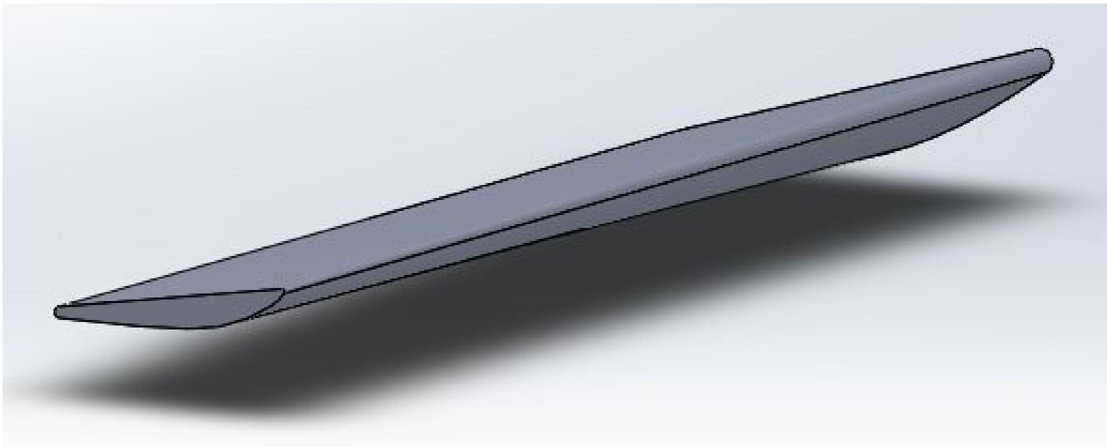
Blade:



Isometric View of Blade (Above), Top View of Detail (Bottom Left), Close-Up of 1 Blade (Below)



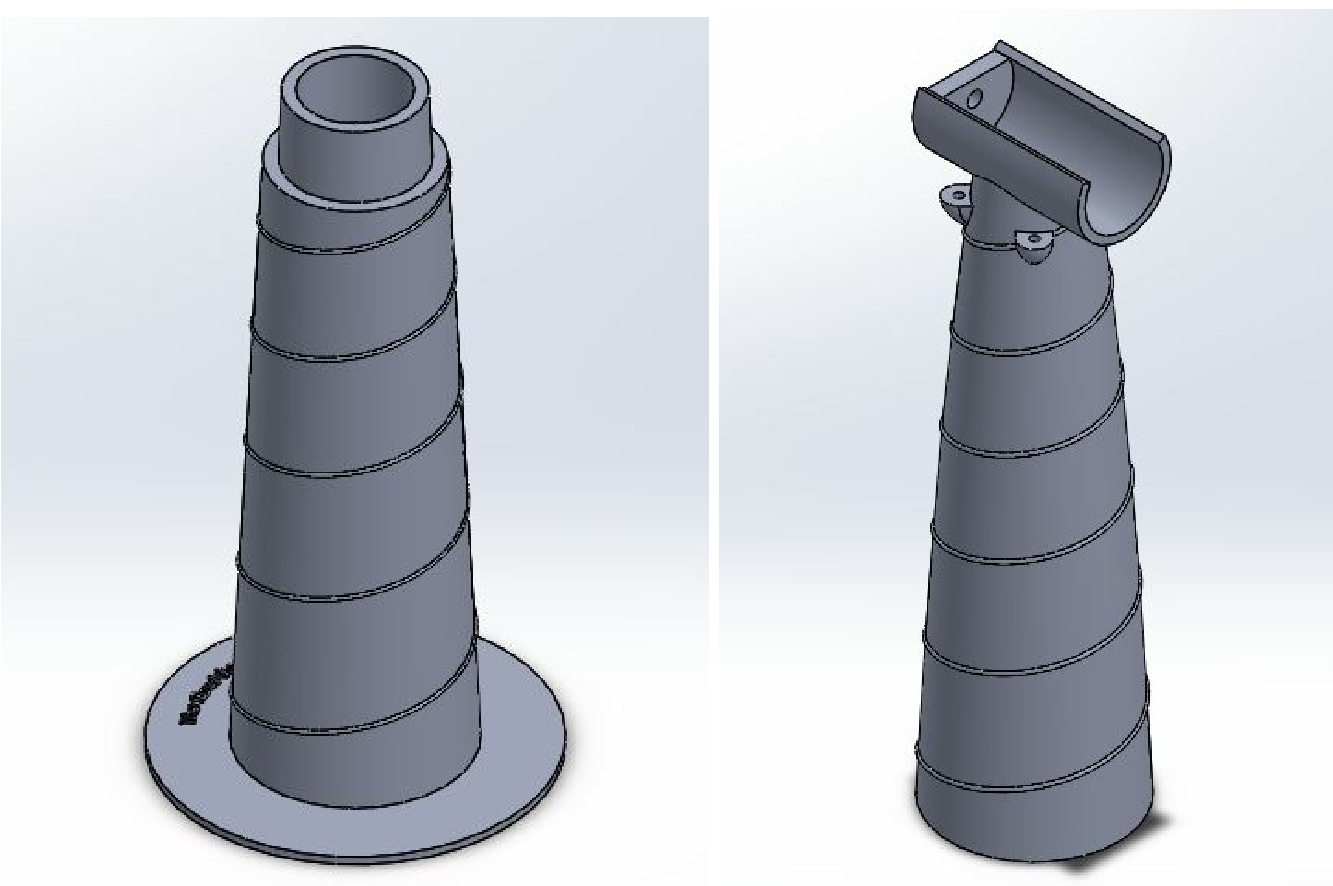




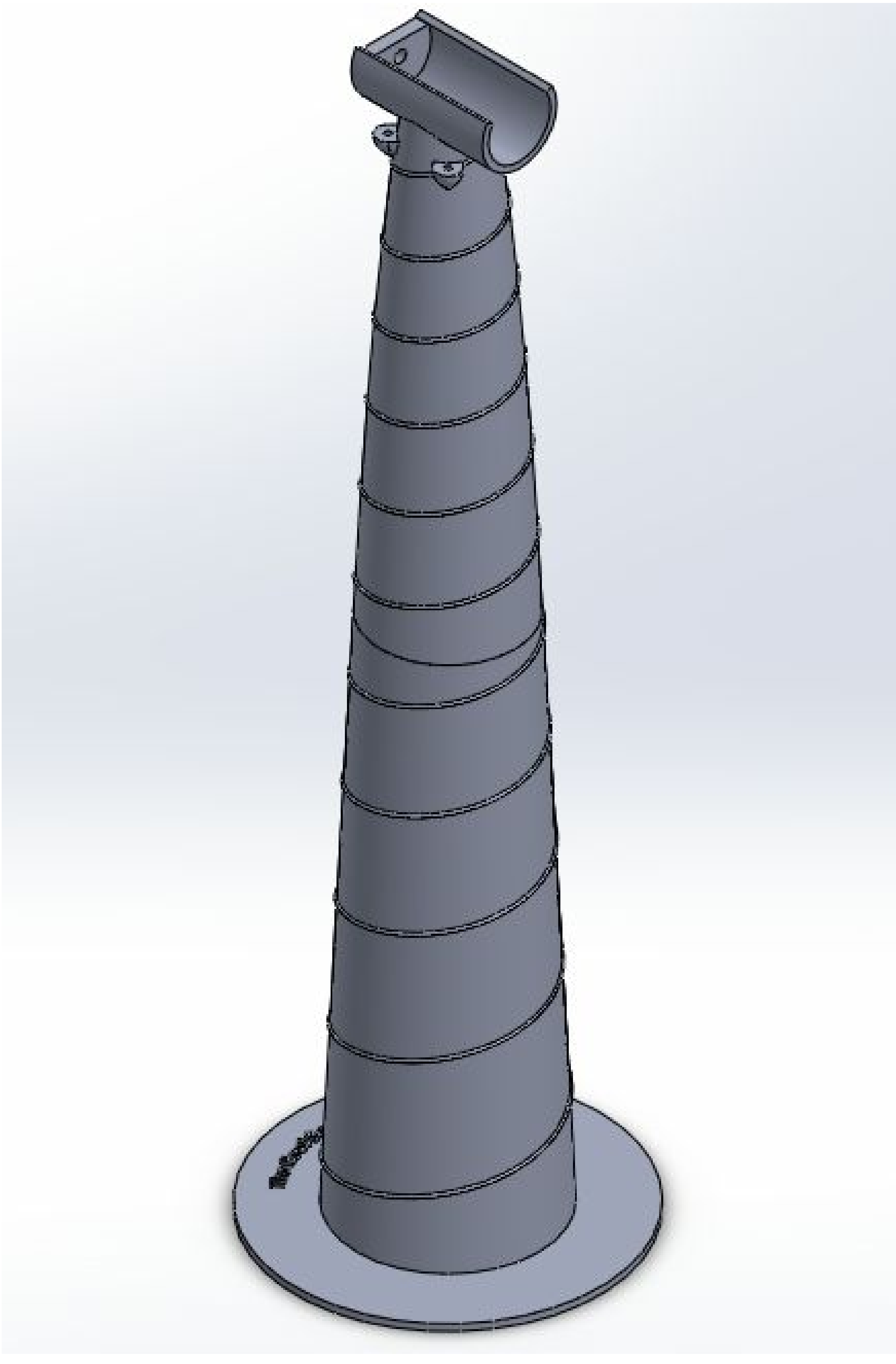
Detail View of 1 Blade

Tower:

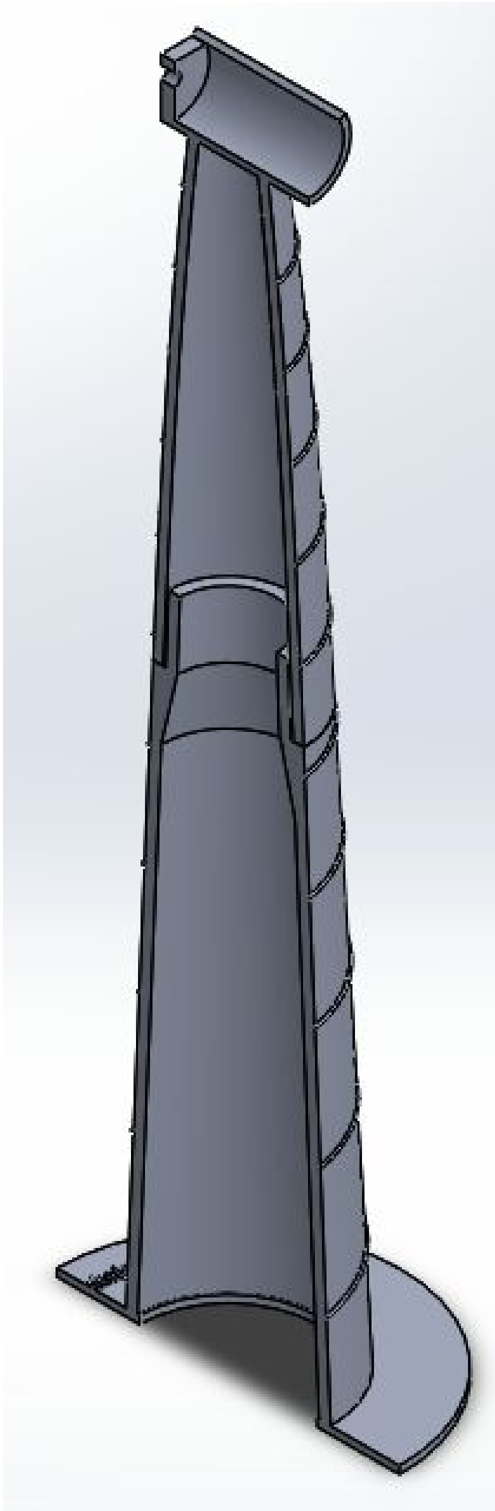
Isometric View of Tower Bottom (left) and Top (right)



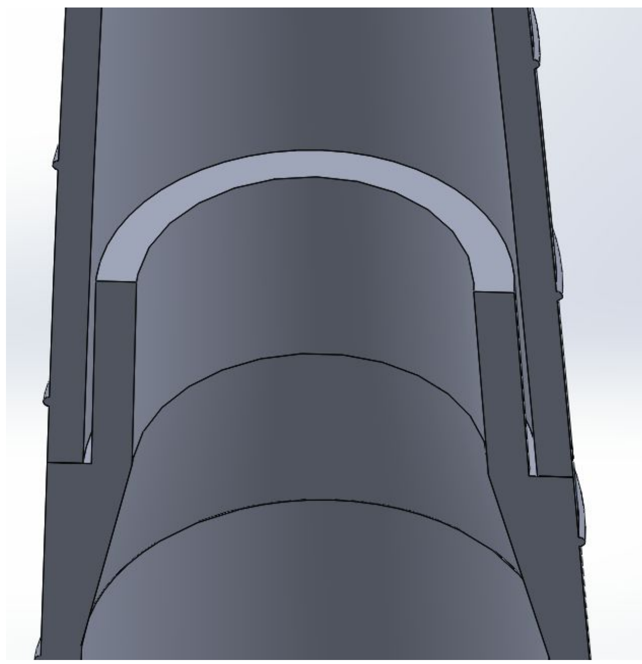
Isometric View of Entire Tower, Top and Bottom, Assembled



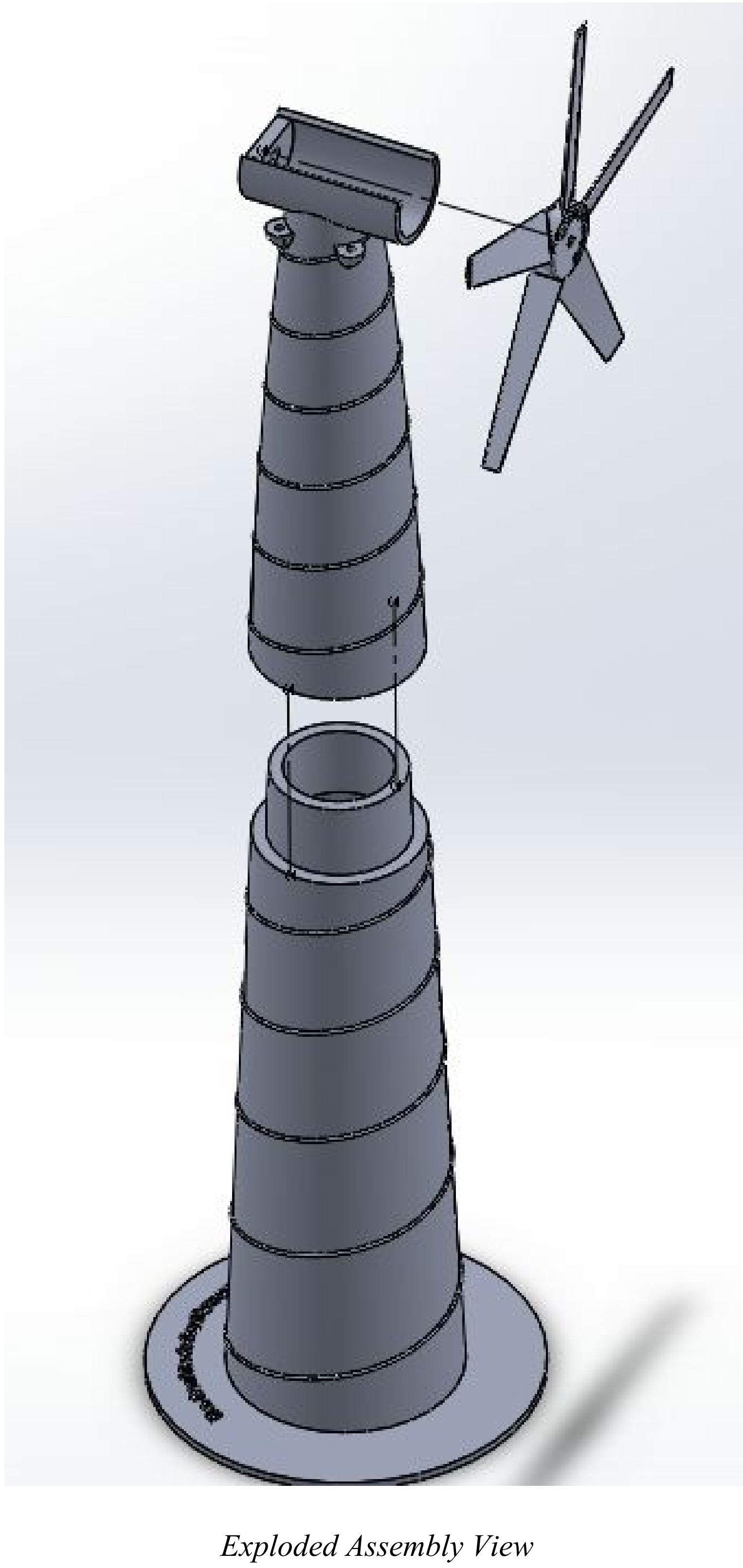
Isometric View of Entire Tower, Top and Bottom, Assembled



Full Tower Section View



Zoom View of Connection Clearance



Exploded Assembly View

CONCLUSIONS

Throughout this project, we developed crucial engineering skills such as technical precision, CAD modeling and manufacturing experience, and a knowledge of the real stress-testing procedures that modeling software's Finite Element Analysis aims to recreate digitally. In the pursuit of optimizing this tower, we experienced the full design process, all the way to 3D printing and constructing our project. In the end, we created a robust five-blade wind turbine with an aggressive angle of attack and narrow, tapered blades that performed well in the power generation stage of the final testing procedure. After data analysis, our blade had generated a maximum power of 1.8545 Watts under the almost 25mph wind speed; it was 19.36% efficient. In comparison, a commercial-grade wind turbine can be between 10% and 30% efficient from initial wind to the output of electricity (Youssefi). Our hollow, tapered, cylindrical tower performed very well in the stiffness category, owing in part to its slightly heavy build as well as its 4 tensioned guylines. Our tower displayed an impressive stiffness of 29.768 Newtons per millimeter, and with a weight of 1.364 kilograms, this achieved the stiffness-to-mass ratio 21.824. There were no major failures of our design, and since it is impossible to fully maximize the two contrasting variables of lightness and rigidity at once, we had to walk a fine line in finding a balance. Overall, our project was not only successful in satisfying the requirements of the assignment; it also succeeded in bringing to life relevant concepts of the class such as FEA, 3D printability and material properties. The process of designing, building, and testing this wind turbine tower made the maximum use of the diverse engineering and practical skills from all of our team members.

RECOMMENDATIONS FOR FUTURE WORK

Ideally our wind turbine would be made of a different material that has a better strength to weight ratio than ABS. This would allow us to create a tower that is both lighter and stronger. However, given the results we witnessed during testing, the guylines were an even more important factor in our rigidity than we anticipated. Seeing this, we could focus more on making strong, tense guylines with a reinforced base-plate and actually hollow out the tower a bit more. One major drawback of our tensioners resulted from the need to make them out of ABS plastic, for lightness and practicality. If we could have made them out of a stronger material, such as aluminum, the amount of creep in our guy wires would have been greatly reduced. In addition, we could not tension the wires fully due to a combination of imprecise tools and a fear that they would snap. Better quality light wire and a good, miniature wrench would be useful for these issues.

Our blades could have benefitted from a higher precision 3D printer; this would allow us to print more precise edges. Our blades needed to have fairly blunt, filleted edges due to the manufacturing tolerances of our printer. In addition, smoother surfaces with fewer visible ridges are more aerodynamic as they resist more drag from the air, leading to a higher efficiency. Also, once a better understanding of fluid dynamics is attained, a more mathematical approach toward blade design can be made. Since a complete understanding of how to optimize for efficiency was not practical, our design process was guided more than we would like by other concerns such as aesthetics, the results of some preliminary testing, and practical knowledge. At the time we did not have a thorough enough understanding of the physics behind what we were doing to take a perfectly scientific approach.

REFERENCES

Gwon, Tae-Gyun. *Structural Analyses of Wind Turbine Tower for 3 kW Horizontal-Axis Wind Turbine.* MS Thesis. California Polytechnic State University, San Luis Obispo, 2011. Web. 13 Oct. 2015.

Youssefi, Ken. “Wind Turbine Structure.” University of California, Berkeley. Cory Hall, Berkeley. 6 Oct. 2015. Lecture

APPENDICES

Appendix A:

Raw data from wind turbine power test:

Voltage (V)	Current (A)	Power (W)	Blade Speed (rpm)
4.14	0.00001	0.01	5704
3.71	0.148	0.57	5487
3.4	0.282	0.97	5300
3.14	0.401	1.28	5130
2.87	0.509	1.48	4919
2.66	0.606	1.63	4771
2.45	0.694	1.74	4663
2.32	0.777	1.84	4470
2.19	0.85	1.87	4399
2.04	0.912	1.88	4111
1.77	1.015	1.82	4036
1.65	1.06	1.78	3933

Raw data from stiffness test:

Test	Displacement (mm)	Load (g)	Load (N)
1	0.01	100	0.981
2	0.05	200	1.962
3	0.07	300	2.943
4	0.09	350	3.4335

5	0.11	400	3.924
6	0.17	600	5.886
7	0.24	800	7.848
8	0.31	1000	9.81
9	0.38	1200	11.772
10	0.43	1400	13.734
11	0.5	1600	15.696
12	0.68	2100	20.601
13	0.83	2600	25.506
14	1.01	3100	30.411
15	1.34	4100	40.221
16	1.7	5100	50.031
17	2.05	6100	59.841
18	2.31	6250	61.3125

Appendix B:

Screenshot of our primary form of Communication: *Slack.com*

Notes: We created a page for our team and organized our communications with the channels "blade", "tower", "general", and "random". This allowed us to share our design progress, bounce ideas off of one another, and schedule meetings. It also served as convenient storage for all of our files, accessible across multiple computers.