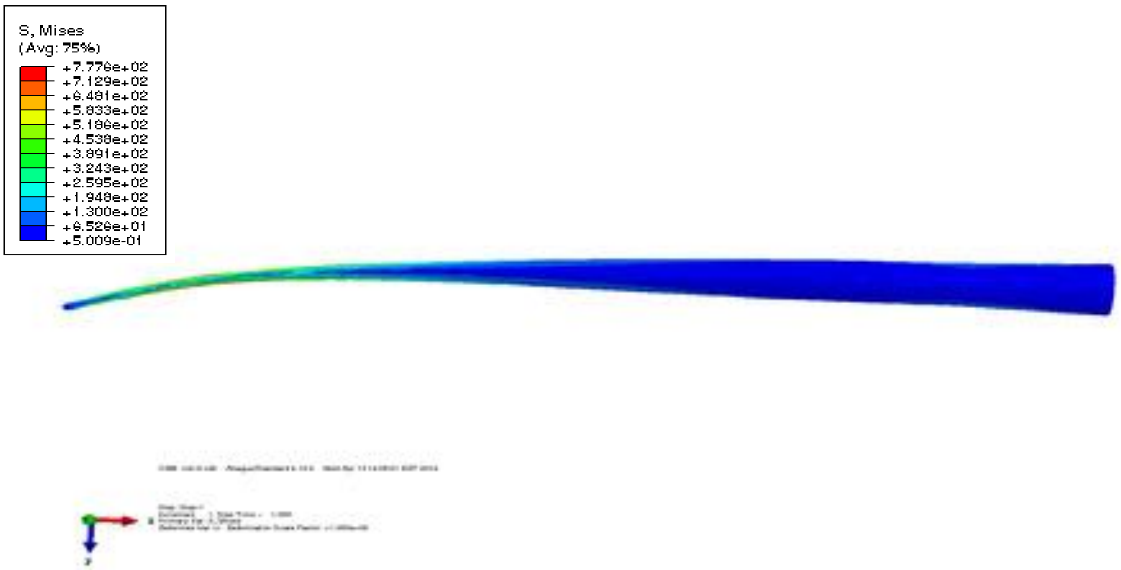
ME 461: Finite Element Analysis

Spring 2016



The Development and Analysis of a Wind Turbine Blade

Group Members:

Joel Crawmer, Edward Miller, and Eros Linarez

PennState College of Engineering

Department of Mechanical and Nuclear Engineering, University Park, PA

Table of Contents

Executive Summary

Imagine a future where everyone has residential wind turbines to produce electricity for themselves. Believe it or not, this future may actually be a reality very soon due to the rise alternative energy. Currently, large wind farms are commonly used in extremely windy locations to create electricity. However, many people are researching ways to increase the efficiency of wind turbines so that they can be used in places that have less than ideal wind conditions.

The goal of this project was to structurally analyze a smaller wind turbine blade that could potentially be used in a residential setting. The proposed blade is similar in shape to the commercial blades, but it is only 1.5 meters long as opposed to the daunting 40 meter length of larger blades. The analysis was simplified by modeling a solid aluminum blade instead of a hollow carbon fiber blade, which is commonly used.

Multiple loading conditions including, a concentrated a small point load, a concentrated a large point load, a frequency analysis, and a distributed wind load, were modeled using Abaqus. The results show that a solid aluminum blade will undergo elastic deformation at small point loads with almost all of the deformation near the tip of the blade. At larger loads, the aluminum blade will plastically deform in a similar manner as the small point load condition. However, the deformation from the larger load was much worse and rendered the blade inoperable. The frequency analysis showed that the two natural frequencies of the blade were 55.47 Hz and 94.6 Hz. These natural frequencies are high and would never be excited by normal wind gusts, but it is important for engineers to know the natural frequencies of the blade design they plan to use. Lastly, the distributed wind load will cause the blade to elastically deform in a different manner than the point loads. When the wind force is distributed along the length of the blade, the maximum force actually occurs near the end face of the blade, where it will be fixed to the hub. The distributed load is perhaps the most accurate model the team conducted and it shows that blades should be designed to handle large loads near the bottom of the blade.

The team concluded that bending is the major failure mode for our model. This conclusion is verified in practical applications because it is known that turbine blades can deflect from wind loadings. However, typical carbon fiber blades are more brittle and tend to fail because of small fractures that quickly propagate. This model only works to visualize and verify the bending mode of failure, but it still provided valuable information about blade failure and the validity of residential turbine blades.

Acknowledgements

The team would like to thank Dr. Kraft for his guidance throughout this project. He provided valuable knowledge about ABAQUS software and modeling advice for the wind turbine. In addition, the team must acknowledge GrabCAD for providing the geometry of the turbine blade.

List of Figures

Section 1: Background and Project Plan

The team will analyze the effects of stresses due to a distributed wind load acting on a simplified wind turbine blade. The goal of this project is to understand the structural integrity of wind turbine blades.

Wind turbines are becoming increasingly common in America as we gradually move towards cleaner energy solutions. An article written by Shaun Campbell for Wind Power Monthly explains that 0.54% of wind turbine blades fail worldwide, resulting in about 3,800 broken blades annually [1]. Since wind turbines are exposed to a variety of elements and load conditions, such as wind loads, even a minor flaw in the structure can cause catastrophic failure. Wind turbines are also quite expensive, costing anywhere from 1.3 to 2.2 million dollars per MW [2]. Thus, it is important to analyze wind turbine blades to reduce the chance of failure during operation. The team's investigation will aid our understanding of the stresses in turbine blades from wind loads and help us make correct design decisions to avoid catastrophic failure.

Figure 1: Blade Failure in a Wind Turbine Blade [3]

The team will begin by getting a turbine blade design from GrabCAD. The team will then generate a high quality mesh for the blade design. If the blade design is too complex for our meshing abilities, we will simplify the design and mesh this simplification. The team will look at a constant load distributed across the length of the blade. The team believes that this load will accurately model a constant speed wind blowing on the turbine.

Section 2: Development and Description of the CAD Geometry

After researching wind turbine blades, the team decided that using an existing CAD geometry, form the GrabCAD website, will result in the most accurate analysis. The wind turbine blade drawing our team chose is shown in Appendix 1.

Wind turbine blades are commonly made out of fiberglass or carbon fiber because these materials are strong, durable, and lightweight. However, it is difficult to find consistent material properties for these exotic materials. To solve this problem, our team will use aluminum as the blade material. A list of material properties is shown below in Table 1. Additionally, the generalized Hooke's law could be used to analyze the blade.

Table 1: 6061-T6 Aluminum Properties [4]

Yield Stress (MPa)	Ultimate Tensile Strength (MPa)	Young's Modulus (MPa)	Density (kg/m^3)	Poisson's Ratio
276	310	68.9	2700	0.33

The external loading conditions that will deform the turbine blade are caused by catastrophic wind speeds produced by hurricanes. In our estimate, we used Category 5 hurricane wind data from the National Hurricane Center [5]. The estimated force calculation is as follows:

$$F = P * A$$

Where,

$$P = \frac{1}{2} * \rho * v^2 * SF$$

The following values were used:

- ρ = density = 1.275 kg/m^3
- v = velocity = 70 m/s
- SF = shape factor
- A = area = l*w

The area is estimated as a rectangular area with length of 1570 mm and width of 168 mm. The shape factor, which is a function of a copious amount of things, can initially be approximated as 0.04 which in turn yields a load condition of about 33 N [6].

Section 3: Development of Finite Element Meshes

The next step of the project, and arguably the most important step, was to develop a mesh for the wind turbine blade. For simplicity, the team started with a tetrahedral mesh. The mesh had a global size of 75 and used defaults for all other options. This tetrahedral mesh is an acceptable starting point for the analysis because it captures the correct blade geometry and does not take a long time to run with only 2,048 elements. However, the large element size does not model the geometry perfectly as evidenced by the faint line pointed out in Figure 3.

In order to increase the accuracy of the simulation, the team decided to create a finer mesh on the turbine blade. The mesh was refined by setting the global size to 25. The resulting tetrahedral mesh contained 12,101 elements; nearly six times the number of elements in our original mesh. This mesh captured the geometry of the blade well at the expense of computation time. However, the simulation time was still small enough to use the refined mesh for all further loading conditions. Figures 4 show the refined mesh.

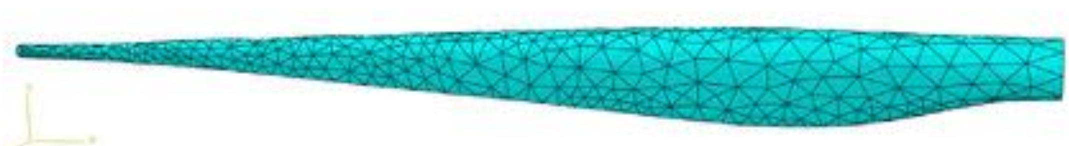


Figure 2: Side View of the Blade Mesh

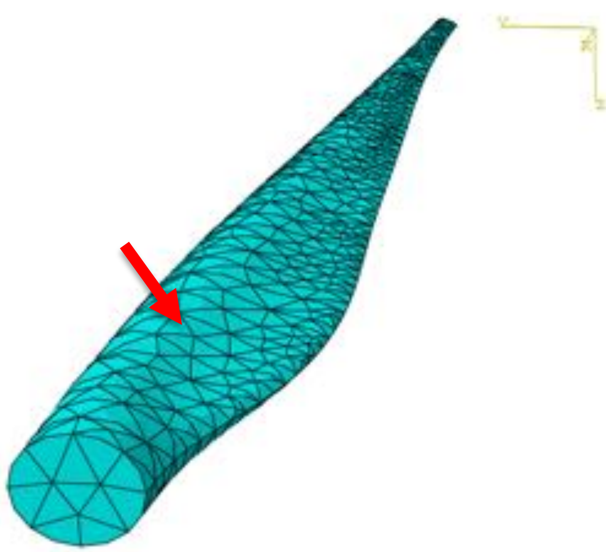


Figure 3: Angled View of the Blade Mesh

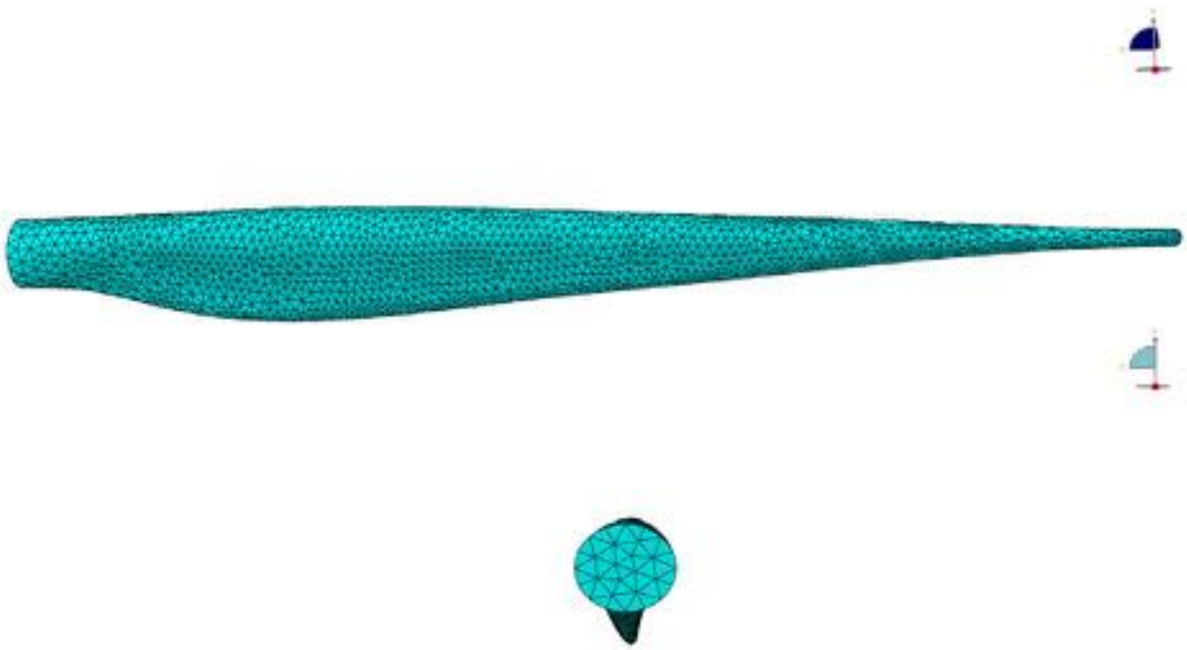


Figure 4: Side and End Views of Refined Blade Mesh

Section 4: Development and Description of the Model Assembly and Boundary Conditions

The wind turbine blade is by itself in the model, so the analysis was performed on a singular part. However, in real world applications each turbine blade is bolted to a central hub that spins to generate electricity. The team used a fully fixed (encastre) boundary condition on the circular end face to simulate a fastened end face. This boundary condition does not allow the end face to translate or rotate in any direction. All loading conditions were performed with only this simple boundary condition.

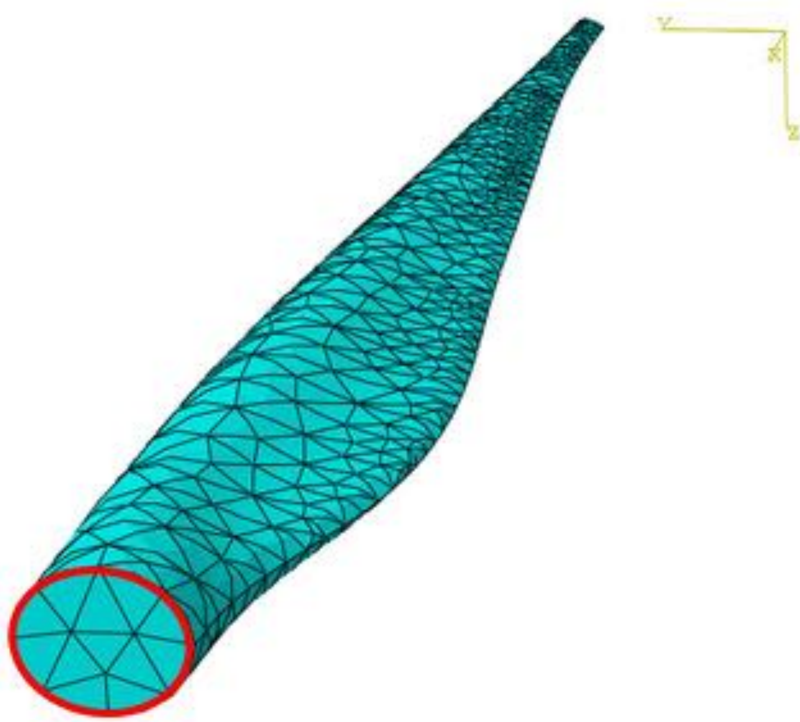


Figure 5: Encastre Boundary Condition on the End Face

Section 5: Development and Description of Model Interactions

The team decided to simulate four loading conditions to see a realistic wind turbine blade response. The first loading condition was a small concentrated load placed on the tip of the blade. This load condition was inspired by the possibility of some small object, such as a bird or rock, crashing into the end of the blade. The team chose to place the load at the tip because it provided the maximum possible moment for the given input force, thus providing the maximum deflection. Figure 6 shows the concentrated load acting at the tip of the blade.

Figure 6: Concentrated Loading Condition of the Tip

The second loading condition is an extension of the first, in that a single concentrated load is placed at the tip of the blade. However, the magnitude of the load is increased by five to model a larger object contacting the blade. This condition could arise if extreme weather caused a massive object, such as a tree, to fly up and hit the blade. While this case is highly improbable, it is still interesting to see the type of response that occurs.

Third, a frequency analysis was performed on the blade to find the natural frequencies from a specific input. Finding these frequencies is important because wind tends to gust in patterns during bad weather, and understanding how the blade responds to these frequencies can help avoid large deflections and possible failure. This loading condition is perhaps the most realistic and informational.

Lastly, the team developed a loading condition to simulate a distributed wind load across the entire blade. This loading condition is different from the point loads because it attempts to model the effects of the wind hitting the entire blade, instead of just at the tip. In reality, this loading condition is very practical because the wind would not be concentrated at one point. The distributed load was generated using a traction force applied in the positive z direction on the front surface of the blade as shown in Figure 7.

Figure 7: Distributed Wind Loading Condition

Section 6: Analysis of Finite Element Model

The small point load condition uses a value of 1000 N placed directly at the tip of the blade. The following contour plots illustrate the loading distribution and the response of the blade to the input load. Also, Figure 9 shows the Stress vs. X-location plot for the loading condition.

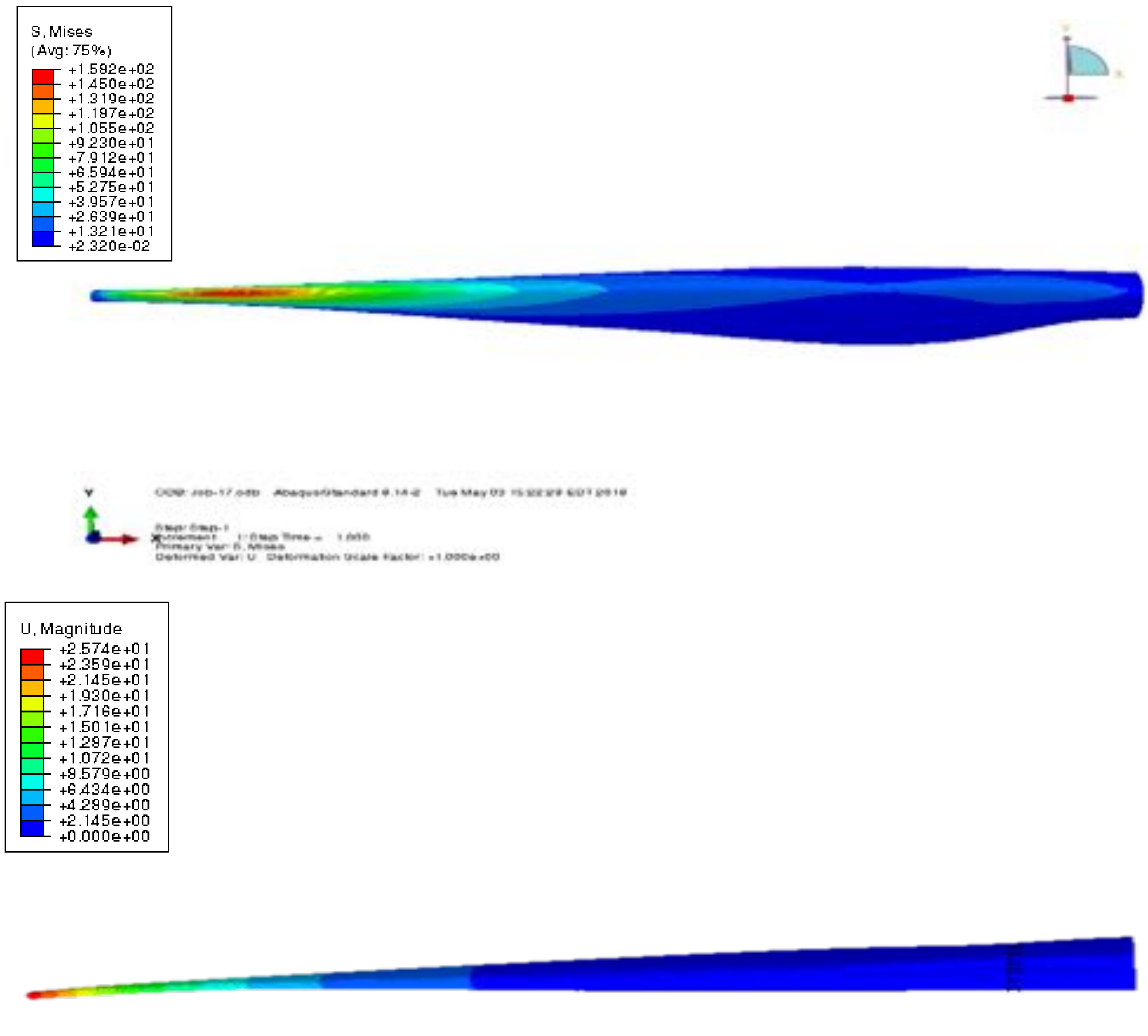


Figure 8: Views of the Response of the Blade to Small Point Load

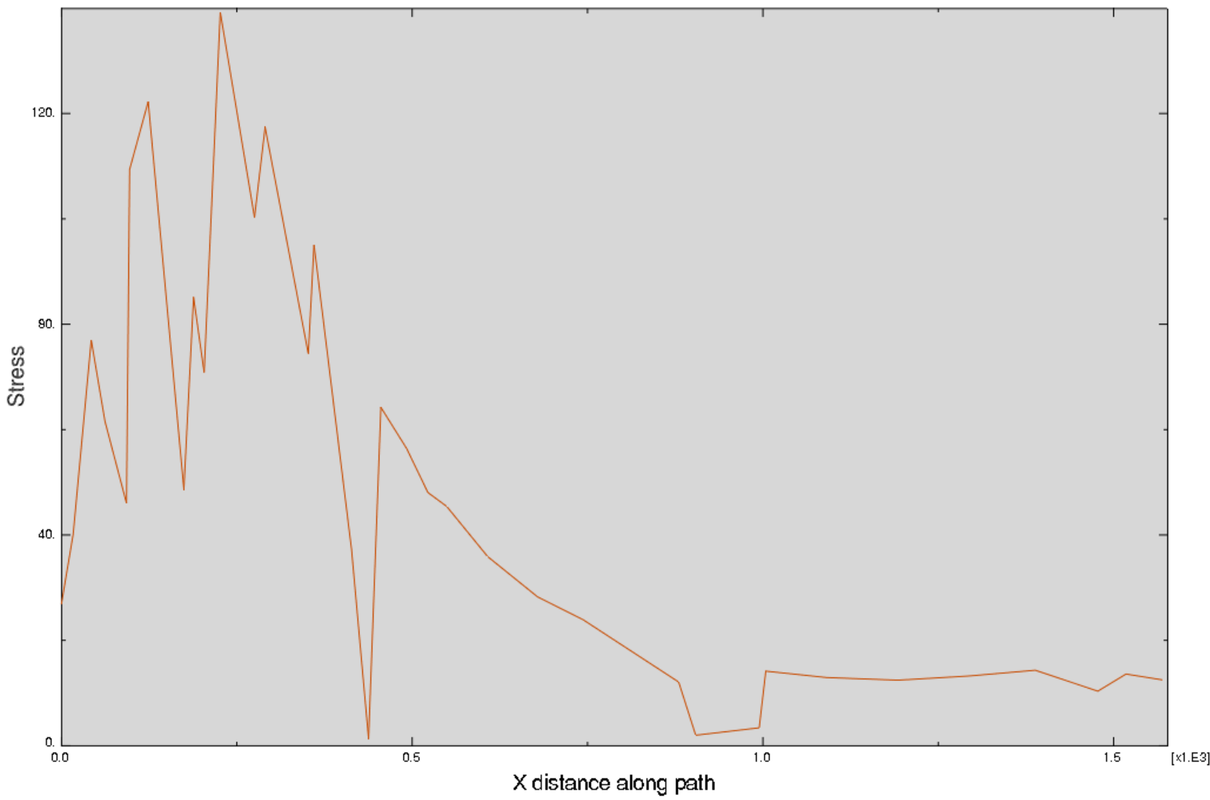
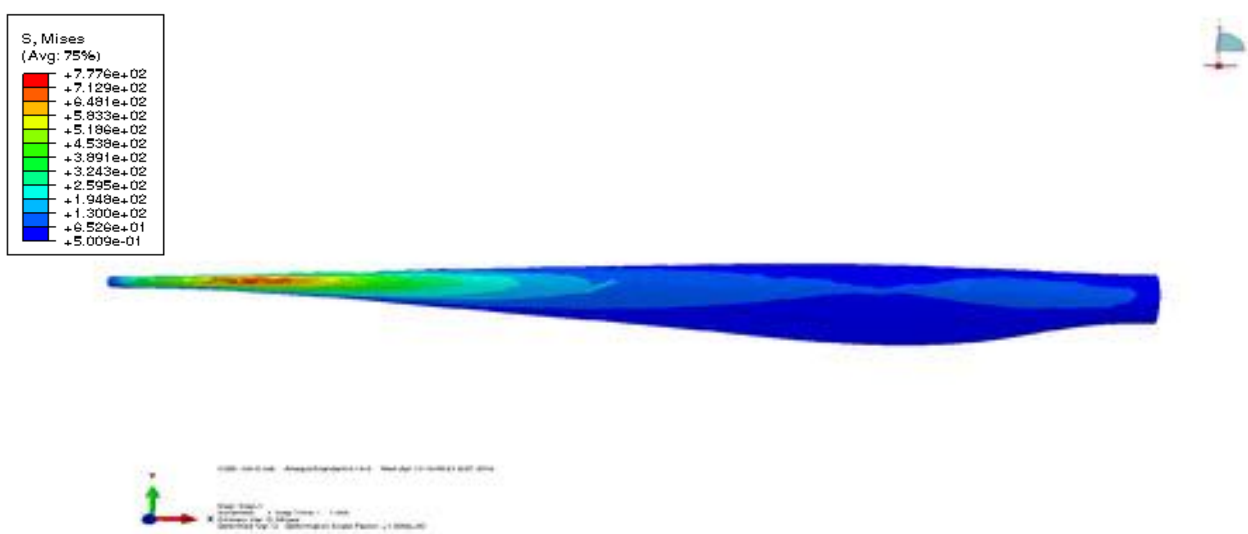


Figure 9: Stress Distribution along the x-distance of the blade

Next, the team ran a simulation with a larger point load, 5000 N that was again placed at the tip of the wind turbine blade. Figures 10 and 11 show the contours plots and the Stress vs. X-Location plot respectively.



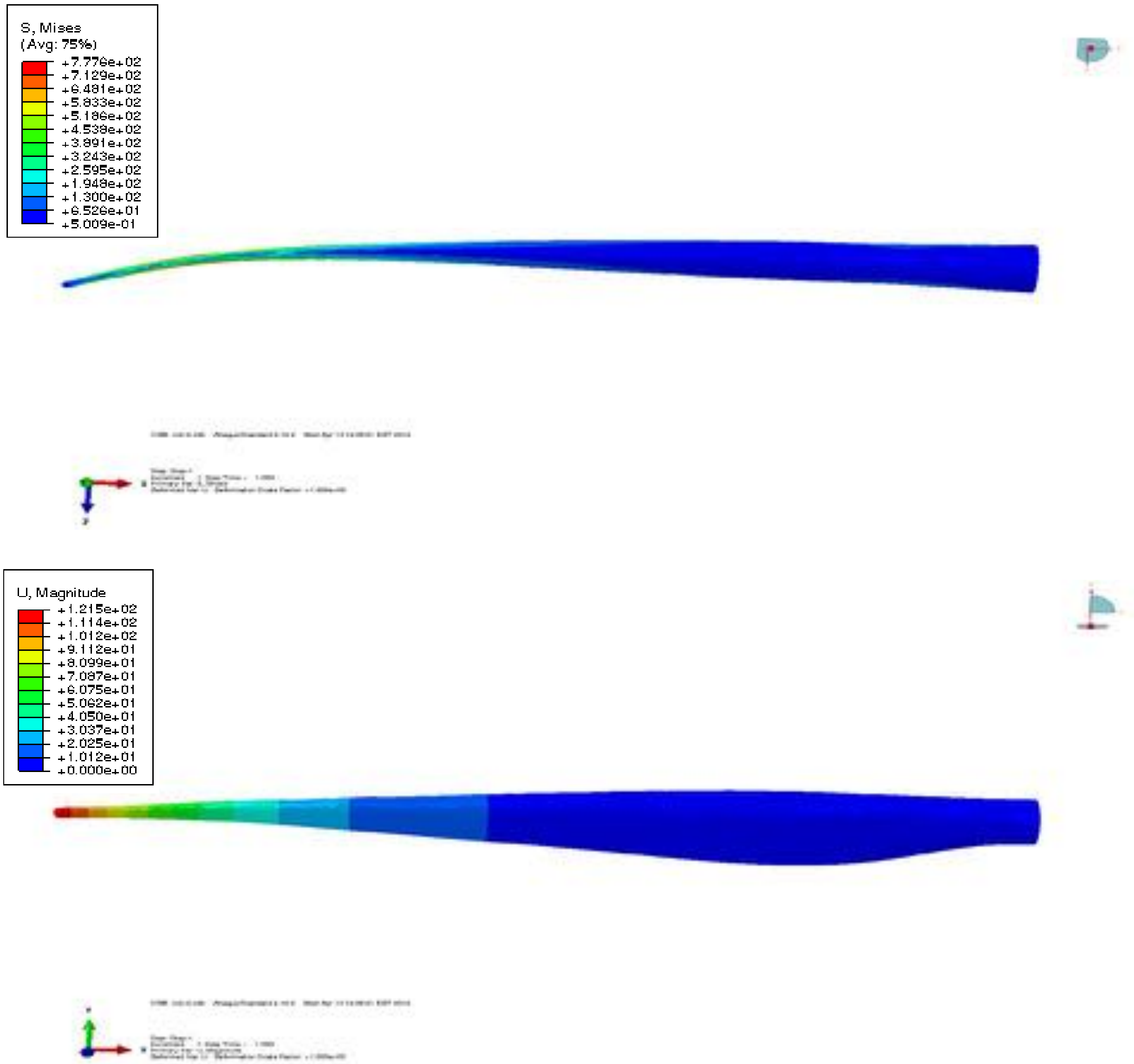


Figure 10: Views of the Response of the Blade to Large Point Load

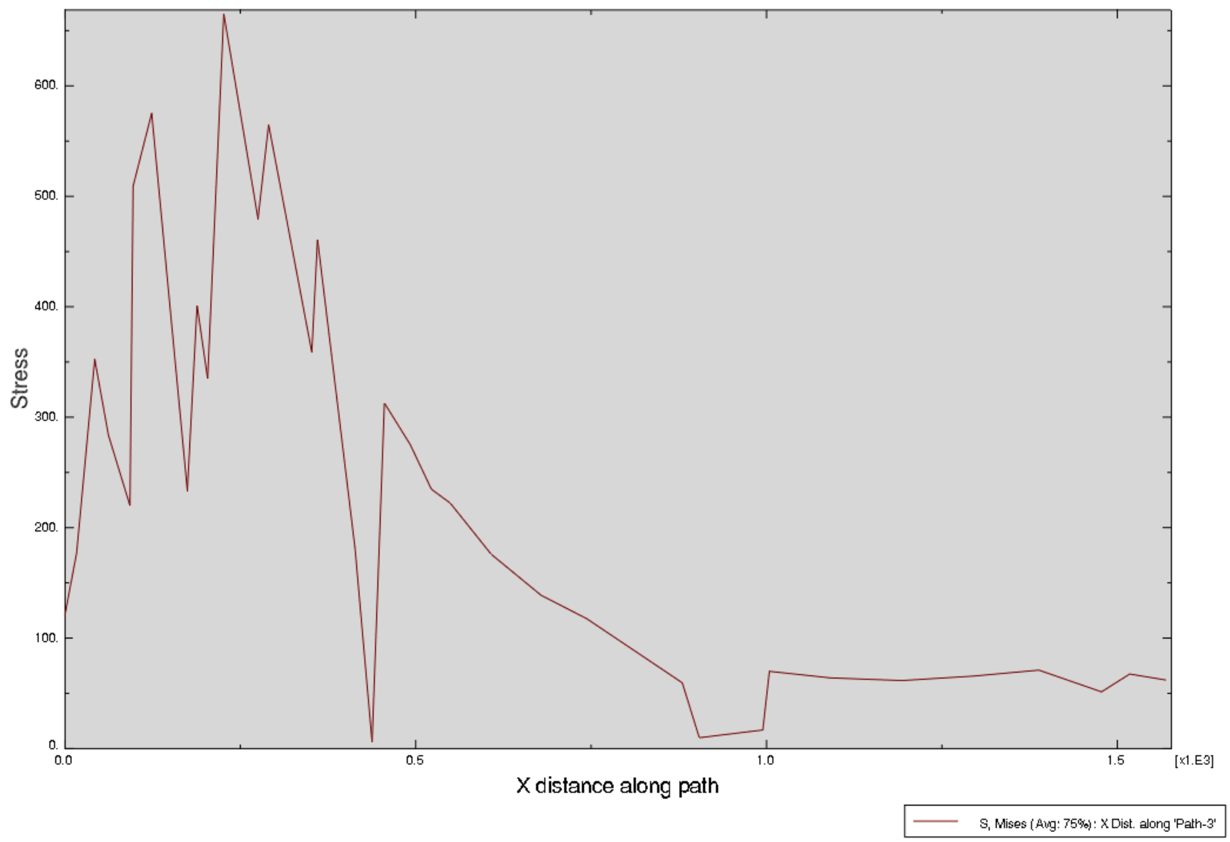
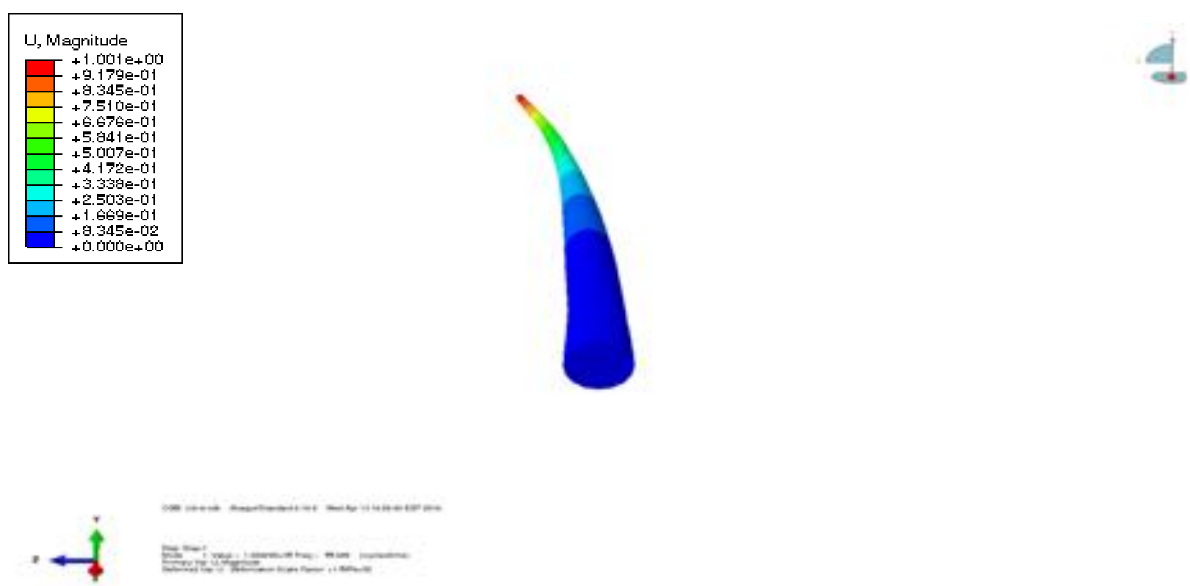


Figure 11: Stress vs. X-Location for Large Point Load

The third loading condition is the frequency analysis. For the condition, a frequency of 100 cycles/sec was used to solve for 10 eigenvalues. Figure 12 shows the contour plots.



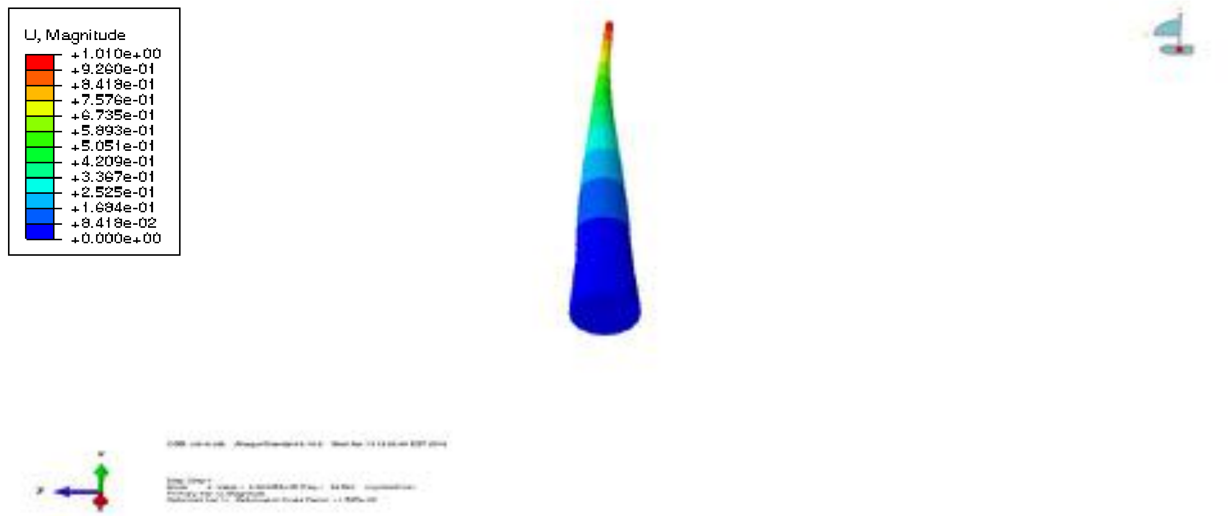


Figure 12: Views of the Response of the Blade to Frequency Input

The last loading condition is the distributed wind loading condition according to a wind velocity of 50 m/s. Using equations found in section 2, the wind speed was translated to a traction force and the following plots were created as a result.

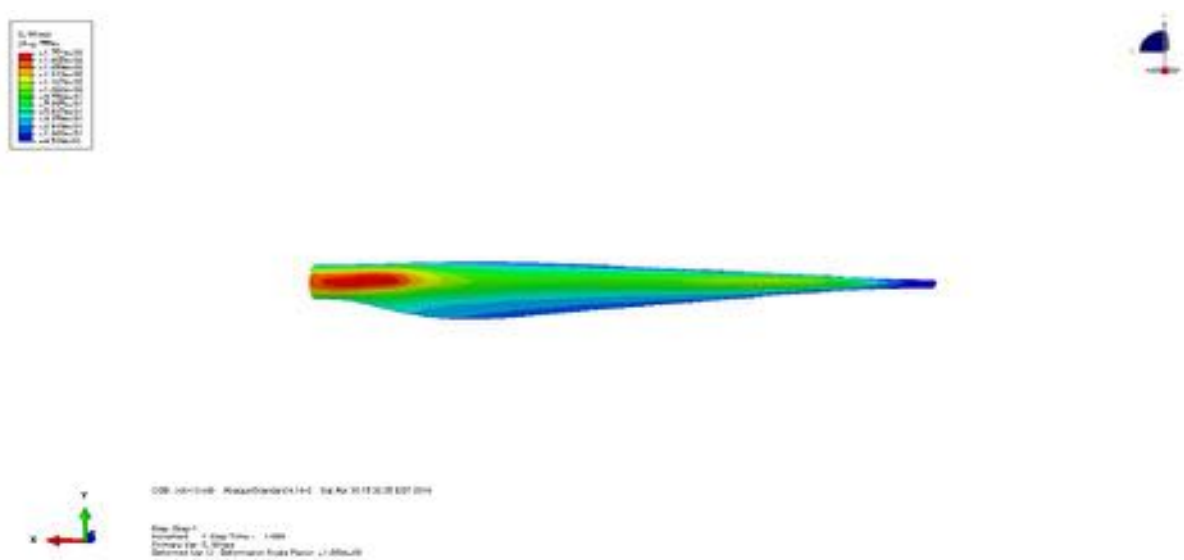


Figure 13: Views of the Response of the Blade to a Distributed Load

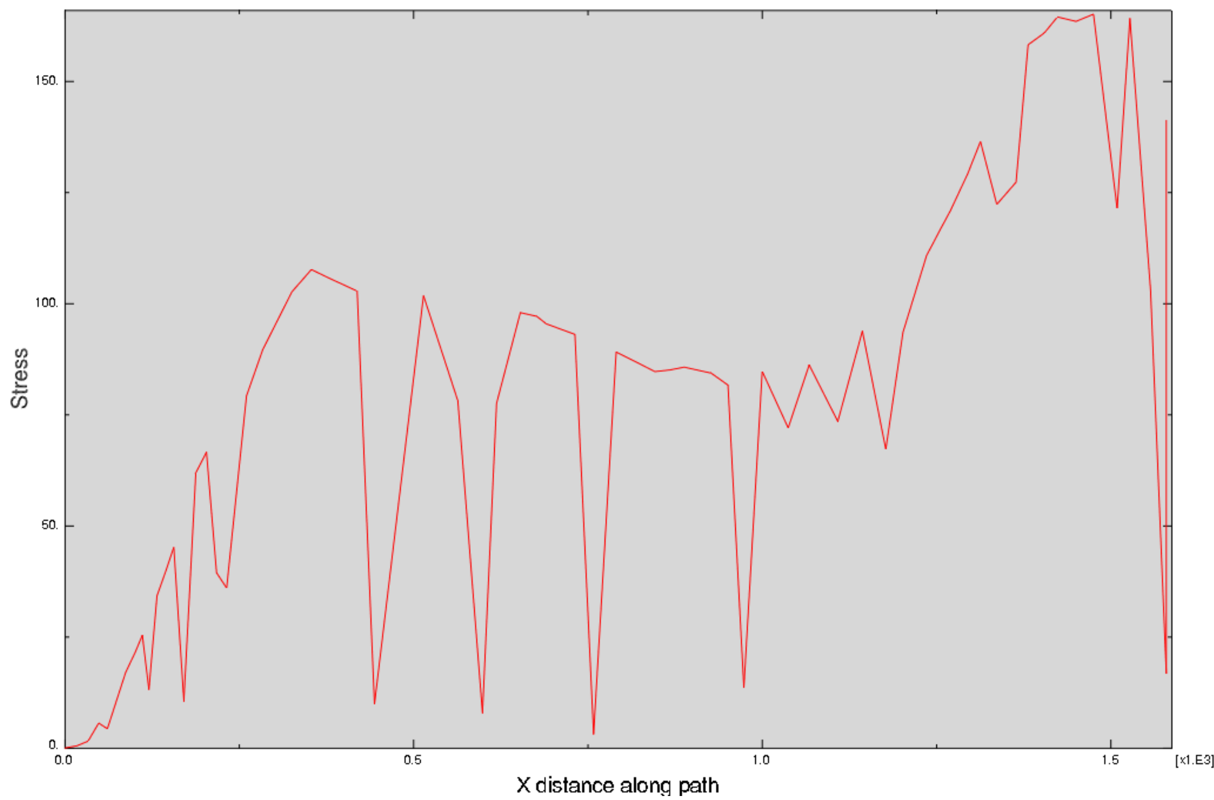


Figure 14: Stress vs. X-Location for Distrubuted Loading Condition

Section 7: Summary of Major Findings

The team analyzed the response of four different loading conditions on the blade: a small point loading condition of 1000 N, a large point loading condition of 5000 N, a frequency loading condition, and a wind distributed load on the entirety of the blade. To reiterate, the small point load was used to simulate a small object such as a bird, hitting the extremity of the turbine blade. At this loading condition, a maximum stress of 159.2 MPa is experienced at a slightly lower location than the tip of the blade. This maximum stress is lower than the yield stress of 276 MPa provided in Table 1, which would allow for the blade to return to its original shape as it does not enter the plastic region. A maximum deflection of 25.7 mm is experienced at the tip of the blade. These results show that for a residential turbine, a load of 1000 N creates minimal deflection on the blade, about 1.6 % of the length of the blade (1570 mm). The next loading condition the team looked at was a larger force of 5000 N. This was to simulate a larger object impacting the blade like a piece of wood or a sign displaced by a violent wind storm. The large force caused a maximum stress of 777.6 MPa inside the blade. Again referencing Table 1 this stress is larger than the yield and ultimate tensile strength showing that if the blade was subjected to this strong of a force it would catastrophically fail. At the frequency loading condition the team was looking for the resonance frequencies of the blade. The team found that the blade had only two resonance at 55.5 Hz and 94.6 Hz. These two frequencies are so high that no naturally occurring wind pattern would ever hit these frequencies. It shows that the blade's designer worked to insure that the resonance frequencies would be very large so that the blade would never be subjected to them. The wind load was to simulate the effects of high speed wind impacting the blade. The wind speed the team used was 50 m/s which is near hurricane strength winds. The resulting load caused a maximum stress of 175.1 MPa which is below the yield stress of the blade material. In the wind load it is interesting to note that the major stress point is at the base of the blade whereas the major stress point in the point loads was near the tip at the smallest cross sectional area. In conclusion the team found that the blade was well designed to survive most real scenarios.

Section 8: Works Cited

1. http://www.windpowermonthly.com/article/1347145/annual-blade-failures-estimated-around-3800
2. http://www.windustry.org/how_much_do_wind_turbines_cost
3. http://ontario-wind-resistance.org/2013/11/23/third-wind-turbine-blade-breaks-in-east-central-illinois/
4. http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA6061t6
5. http://www.nhc.noaa.gov/aboutsshws.php
6. http://projects.knmi.nl/hydra/faq/press.html

Appendix 1: Engineering Drawing: Blade