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12/11/2022

Date

Title: Solar Panel Canopy Stress

by

Name: Terrell Elias Marler

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submitted in partial fulfillment of the requirements

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to

The Honors College

of

The University of Alabama in Huntsville

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Honors Capstone:

Solar Panel Canopy Stress Analysis

By Terrell Elias Marler

December 9th, 2022

Abstract

This project intends to investigate the efficacy of solar panel canopies over Walmart parking lots in multiple parts of the US. The previous section to this project showed profitability, but this section intends to show physical stability of the structure through different types of wind loads on the solar panels themselves. The solar panels will be high into the air above where the cars would theoretically be, and therefore, they will be exposed to high wind loads on the foundation and on the supporting rod that will be holding the solar panels up. Because different parts of the country have different peak wind speeds such as frequent hurricanes coming through the southern states, there will be different loads on the supporting beams. This project will use hand-validated finite element analysis to look at the previously selected product called SunPower Helix T-Type Carport and do structural analysis to check how different wind loads affect the stresses created in the carport.

Introduction

As the need for power grows with industries like Tesla, Amazon, and Meta, the demand from the market for power generation grows with it. However, with increasing pressures from society to be carbon neutral or carbon negative, solar panels are a great approach. Many companies today purchase land specifically for solar panels, but with the increasing real estate costs in Huntsville and the surrounding areas, it is becoming less and less cost effective to buy the land. However, there is an area of land that every company, small business owner, and even local household owns: parking spaces.

It may be relatively easy to construct a small roof over their parking spaces, and the benefits would be twofold: it would generate electricity for selling back to the grid or using at their building, and it would be shade for the cars that needed to park underneath. Selling the electricity to the grid or using it to power their buildings would increase profits month to month, and it would certainly have a huge impact as time goes on. Additionally, with the high temperatures in the South, people try to park in the shade so that their air conditioning does not have to run on full blast for the first few minutes when their car inevitably heats up after hours of parking in the sun. A common idea for people in the heat would be to park under a tree as this solves the problem. The issue with this is that it drops sap, bird droppings, and leaves on an individual's car. This would solve every problem with parking.

With carbon taxes growing around the world, having a system to reduce emissions would be extremely beneficial for the bottom line. As of 2021, there are 35 carbon taxes around the world, and as they are mostly in developed countries, there will likely be a carbon tax introduced in the US soon. Especially in state law, carbon taxes are already passed in several states, making it more difficult to keep within profitable margins for certain companies that were used to emitting massive amounts of carbon without repercussions.

Additionally, with high speeds from hurricanes that have happened recently in the Gulf of Mexico and the Atlantic into states like Louisiana, South Carolina, and North Carolina, a future investor would want to make sure their investment will last for the full period that it would take to pay off: about 15-25 years in the cases tested. If a Category 2 hurricane comes in with 100 mph winds, the owner would want to make sure their massive investment is not going to become worthless. Especially if a bigger hurricane comes through, there could be massive losses. Every

year, millions and billions of dollars are lost due to structures breaking in high wind speeds, and this project will determine whether the canopy will be one of them.

With these reasons and the previously shown financial viability, there are many reasons to move towards a solar panel parking lot canopy. However, there is uncertainty that the structure will stay stable through all kinds of conditions. This project will use several assumptions: the foundation of the canopy itself will remain stable, the supports and bolts are made of steel, and that the only forces from the wind on the panels are lift and drag. This will use finite element analysis using Patran and Nastran to find maximum Von Mises stress all the way through the model.

Methodology

The first step is to find the dimensions of the parts of the supports and the solar panel canopy. It is documented that the canopies use SunPower 450W 22.2% Efficient Panels. These panels are documented have 72 cells in a 5 by 16 setup. Each cell is 125 mm by 125 mm. This means that each panel is .75 m by 1.5 m. The SunPower T-Type Carport is 15 x 5 solar panels for overall dimensions of 12 m by 7.5 m (SunPower). The SunPower Helix Carport is adjustable between 10-14 feet high. However, as the standard 18-wheeler is 13.6 feet tall, it can be assumed that the average owner of a Walmart would opt for the 14 foot or 4.27 meter tall option at installation. As discussed in the previous report, the ideal angle that the solar panels would be tilted at would be 34.7° south towards the equator.

The solar panel itself (excluding the supports) is documented to have been tested in 2018 to support a maximum moment of 574 kip-in in the beams running across the bottom of the panels. Below is an image of the solar panels in the stress analysis before fracture (Bapat).

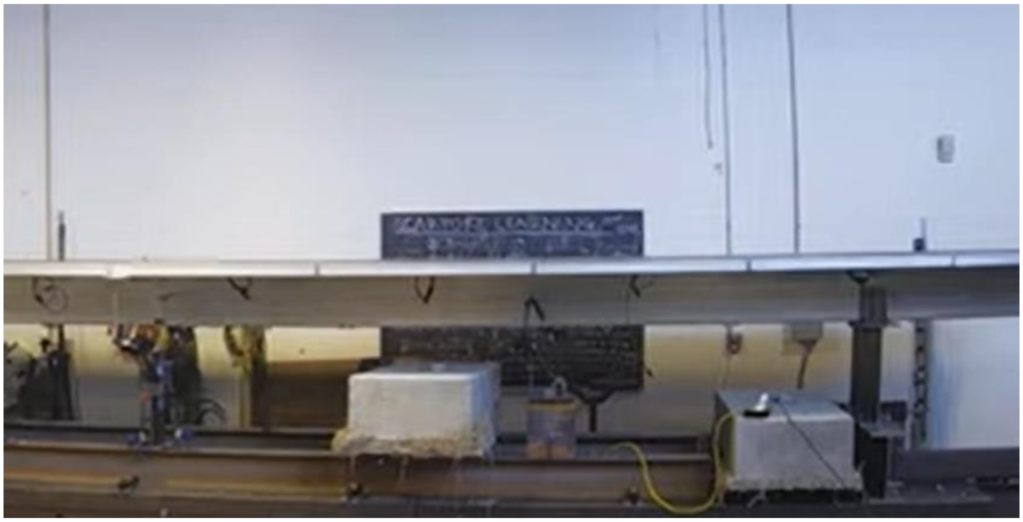


Figure 1: Screenshot Deflection Test on Panels (Bapat)

The documented load at failure is very small compared to what could be generated from the wind. This means that a potential point of failure is at the solar panels themselves. The method of failure seems to not be in the beams going across the bottom of the panels, but in the panels themselves, as can be seen in the video. The flexing of the of the bar caused the panels to break. The moments on the panels from wind will be calculated by hand and plotted as a function of wind speed. Then, at a wind speed of 100mph, an finite element model will be created in Patran and analyzed in Nastran to verify the hand calculations and validate the model for the whole spectrum of speeds.

After the maximum speed is calculated for the solar panel itself, it is necessary to figure out if the supporting beam that goes from the solar panels into the foundation will fail before the solar panel itself. The solar panels will initially be created, and then it will be attached to the rest

of the model for further evaluation. If the model with everything attached gets to the yield strength of steel before the solar panels break, the failure point will not be the panels themselves.

The peak wind speeds recorded in a year period around the country as shown below range from 62 to 98 mph. This means that any solar panel canopy designed should be able to withstand wind speeds of above 100 mph at least. If a hurricane came through with even faster wind speeds, the design necessary will be shown in charts to be able to withstand any wind speed one could need.

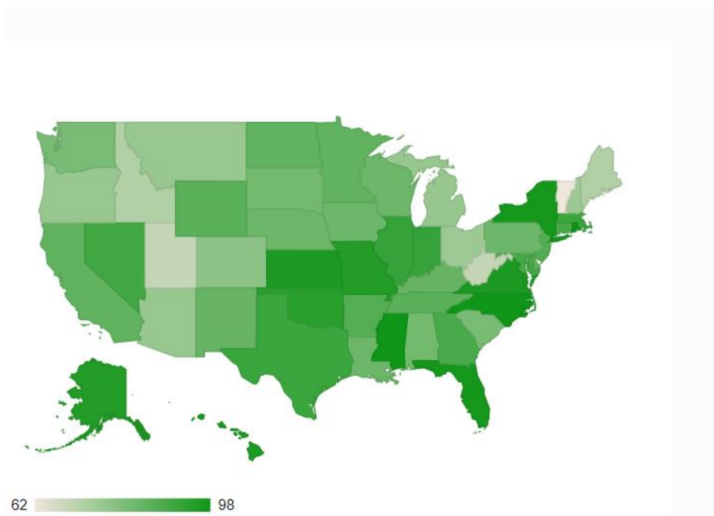


Figure 2: Map of Peak Wind Speeds across the US (Climatic Wind Data)

Calculations

Using the documented failure moment on the canopy, a 2D distributed load will be placed on top of the solar panels from the wind to see at which wind speed the solar panels will break. Below is the picture of the solar panels:

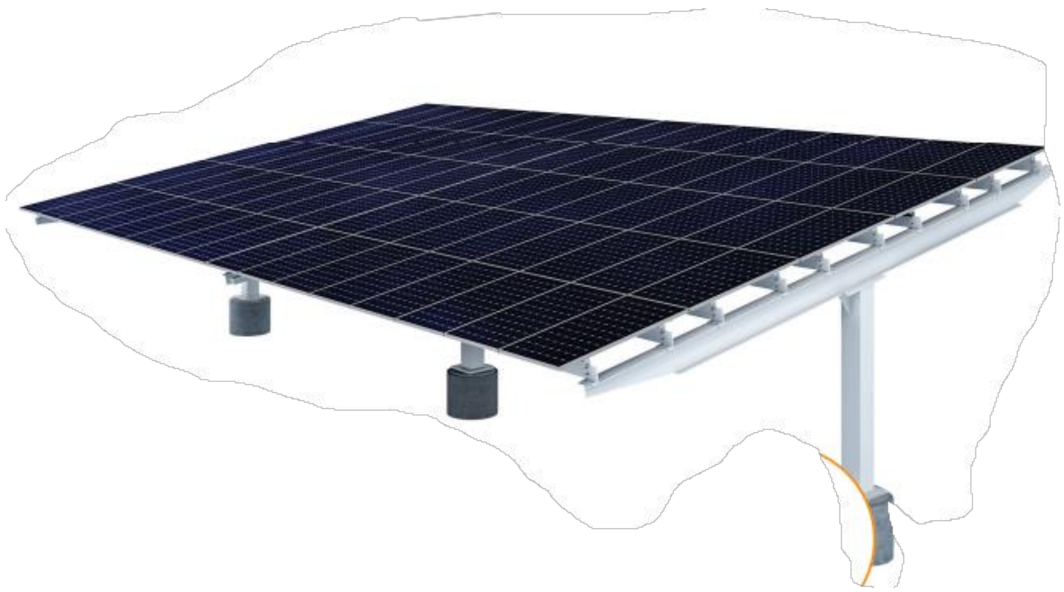


Figure 3: SunPower T-Type Solar Canopy (SunPower)

To make modeling of just the solar panels easier, the canopy will be simplified to just be one of the sides, with supports on either side. This means that only from the middle support to the right will be used in the modeling. From the middle over is 236 inches by 295.2 inches The longer edge is the one with the supports.

To find the wind speeds, the NASA documentation on kites will be used (Kite Drag Equations & Kite Lift). So, the flat plane at an incline will be modeled as a kite to ease calculations. The lift is the force from the wind perpendicular to the flow direction, and the drag is the force parallel to the flow direction. The flow is assumed to be flowing directly into the panels. The necessary equations are:

$$C_{lo} = 2\pi a, where\ a\ is\ the\ angle\ of\ incline, 34.7\ degrees\ or\ .6056\ radians\ (1)$$

$$C_l = \frac{C_{lo}}{1 + \frac{C_{lo}}{\pi AR}}, where\ AR\ is\ the\ aspect\ ratio\ (2)$$

This means that $C_{lo} = 2\pi * .6056$=3.81, and C_l=2.04. C_l is the coefficient of lift.

Next, the coefficient of drag, C_d, needs to be found.

$$C_{do} = 1.28 sin(a)\ (3)$$

$$C_d = C_{do} + \frac{C_l^2}{.7\pi AR}\ (4)$$

This means that $C_{do} = 1.28 sin(34.7) = .729$, and $C_d = .7287 + \frac{2.04^2}{.7\pi * 1.4} = 2.08$

To convert from coefficient of drags and lifts, the following equations are used:

$$F_{drag} = C_d A\rho \frac{V^2}{2}, where\ \rho \text{ is the density of the air } (5)$$

$$F_{lift} = C_l A\rho \frac{V^2}{2} (6)$$

The density of air that will be used is $.0765\ lb/ft^3$ (Will V).

The air speed of 100 mph will be used in the finite element model, and the hand calculations at this speed will be compared to the finite element.

The values found is $F_{drag} = 472kip$, and $F_{lift} = -463kip$. This is evenly distributed across the panels. This means that the angle of the net force on the solar panels is 79.2 degrees, almost perpendicular. The forces are close enough to perpendicular that the hand calculations will initially be modeled as a pressure acting perpendicular to the panels, and the force used will be: $|F|sin(79.2) = 650\ kip$, evenly distributed across the panels. The finite element model will have two load cases, one with the pressure to compare to the hand calculations, and one with the force as the vector it actually is to compare to the other answers. A diagram to better visualize the project is below with the red arrows being the support reactions:

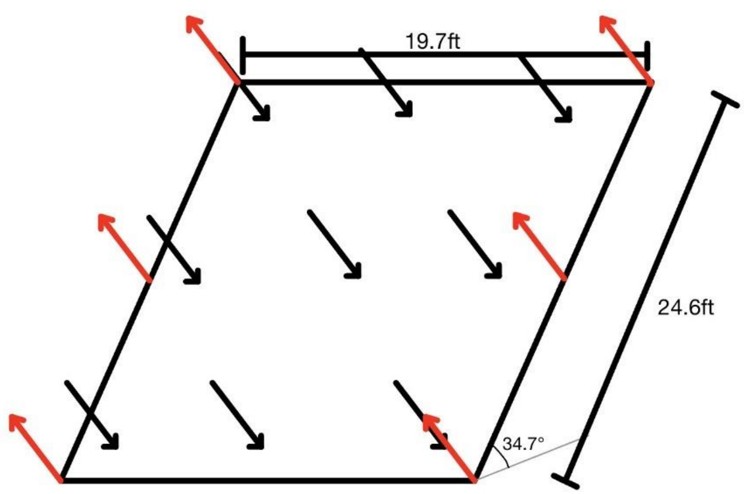


Figure 4: Distributed Force Diagram

This can be simplified to a distributed load:

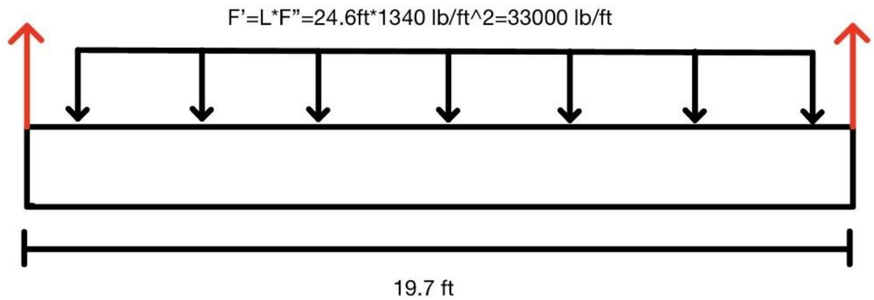


Figure 5: Distributed Load on Panel

From this, shear and moment diagrams can be created:

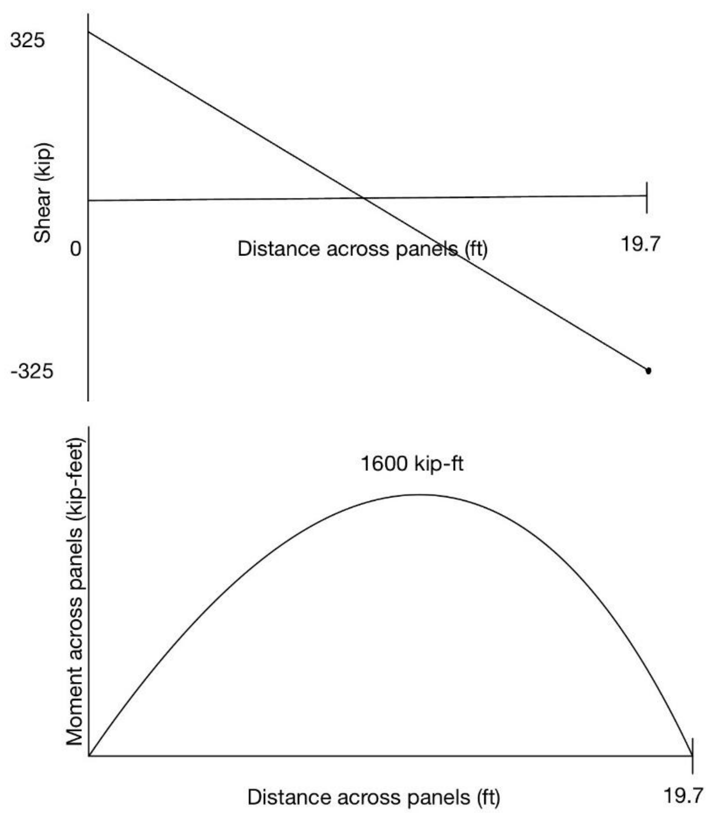


Figure 6: Shear and Moment Diagrams across Panel

The parabolic shape of the moment diagram shows a peak halfway through the shape with a peak moment of 1600 kip-feet or 19,200 kip-in. To verify these calculations, finite element analysis is

done. Below is a picture of the Von Mises stress and deformations of purely the component of the force that is normal to the panel.

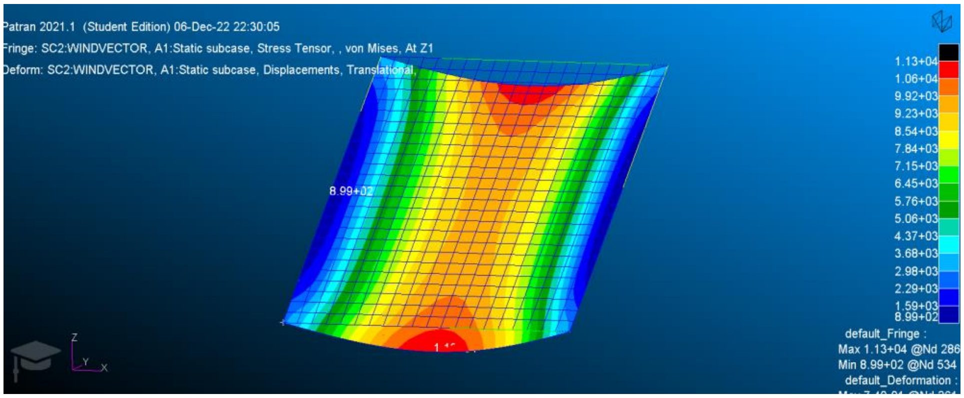


Figure 7: FEM Output with only Normal Pressure

Because other forces are present, the total load vector was also used, but these will not be compared to the hand calculations. Because these include slightly different and higher force vectors, the stress is slightly higher in the version done with total force vector:

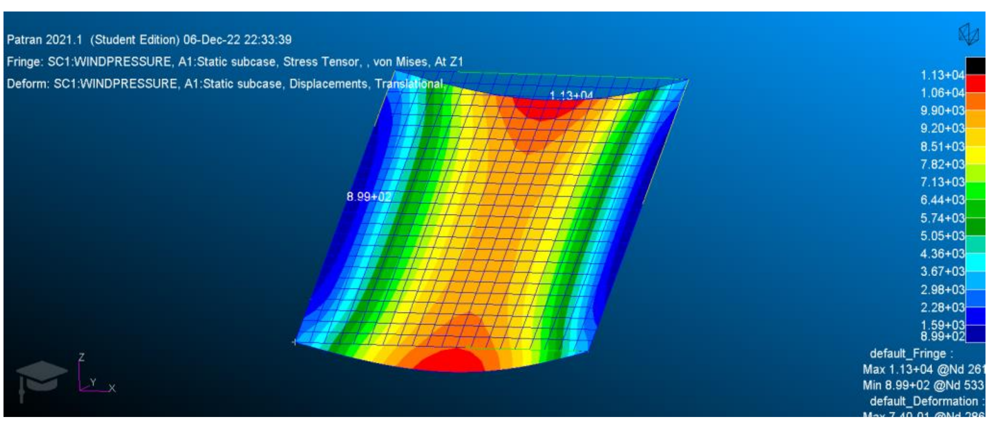


Figure 8: FEM with Force as a Vector

The fringe on the right is stress in psi. It can be seen that the average stress across the center of the panel on the first graphic is about $9.5(10)^3$ psi. However, these stress values do not mean very much. This is because to get an output on Nastran, a thickness of the sheet needed to

be entered. This is because Nastran does not calculate moment and shear diagrams, but stress for each element. The thickness entered was 6”. To obtain the moment at that point, the stress and dimensions of the sheet can be used using the following formula:

$$\sigma = \frac{Mc}{I} \quad (7)$$

$$\Rightarrow \mathrm{M} = \frac{\sigma \mathrm{I}}{\mathrm{c}}$$

Where c is the distance from the neutral axis, I is the area moment of inertia, and σ is the stress.

For a beam that is 24.6 feet by 6 inches, the moment of inertia is $\frac{1}{12}bh^3 = 5313.6in^4$. $c = 3"$ because the stress at the outside of the beam is what is important. So, the moment is $9.5(10)^\wedge 3 * 5313.6/3 = 16{,}800\ kip - in.$ This is a 14% error from the hand calculations, but due to the wide ranges of stresses over the center of the beam and selecting a general average, the 14% error is expected. This validates the model used in the hand calculations, and it will be used to create a curve of maximum moment across all speed ranges of the wind. Below is the

graph of that information with a second curve denoting the maximum sustainable moment in the solar panels.

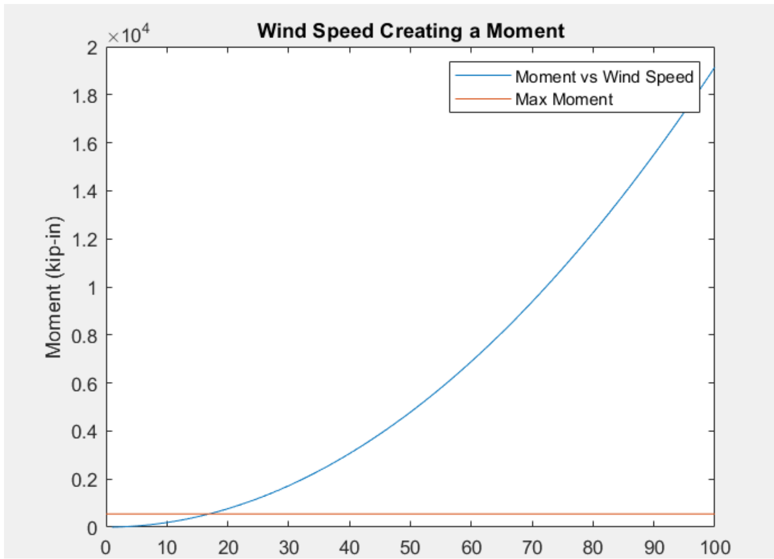


Figure 9: Graph Showing Moment at Different Wind Speeds

The intersection of the actual moment against the maximum sustainable moment is at 16.9 mph. This means that the failure point of the panels is when wind at 16.9 mph hits the panels. Once again, the failure point was not the beams supporting the panels, but the deflection in the beams causing the panels to hit against each other and breaking. This is poor design.

However, changing the angle of the solar panels can affect the maximum wind speed that the panels are able to sustain. The maximum speed at 34.7° is 16.9 mph, but at the expense of

efficiency of the panels, the maximum speed can be increased. Below is a graph of the maximum speed that the panels can sustain at each angle of incline:

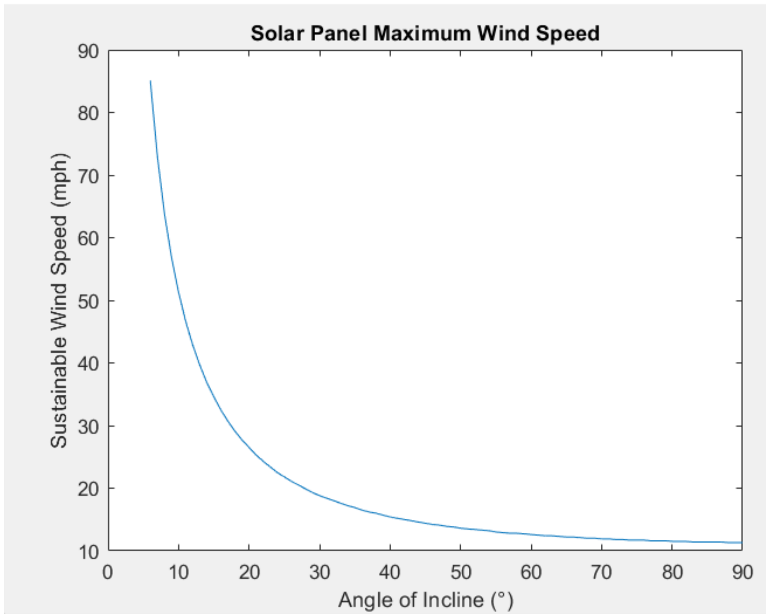


Figure 10: Graph Showing Max Wind Speed at Each Angle of Incline

The wind speed gets very high as the angle of incline decreases. Values over 100 mph were deleted as they will not be necessary for the results. This means that the first viable angle of incline is 6°.

The next step in the calculations is to calculate how much stress is created in the support beams themselves. These are the beams that support the solar panels from the ground. As discussed above, the beams must be tall enough to create 14 feet of clearance from the ground from the bottom of the solar panel. This means that as the angle of the solar panel increases, the height of the supports must be adjusted. Once again, hand calculations will be made, and they will be verified for a certain value using the finite element software Patran and Nastran.

The first step is to find the dimensions of the beam that supports the solar panels from the ground. This will be done using pixel counting. Using pixel counting and the Pythagorean Theorem on Figure 2, it can be shown that the supporting beam is a square hollow section with dimensions 8"x8" (Appendix 1). However, it is not clear how thick the walls are. The different area moment of inertias for this beam shape is listed on Engineering Toolbox, and they range from 146 in^4 for a 5/8" thick wall to 54.4 in^4 for a 3/16" thick wall. To start, the conservative 54.4 in^4 will be used in calculations and FEA modeling. If it appears that the beam will yield, a higher moment of inertia can be used.

To calculate the reaction forces at the base of the supports, the finite element model will be used at 50mph. Because there are three support reactions, one from each beam, and all in a line, this setup is statically indeterminate, and the model will be used to figure out what will happen at each of the support reactions. The solar panels will once again be modeled using 6" thick steel 2D elements, with a Young's Modulus of $30(10)^6$ psi and a Poisson's Ratio of .3. The support beams will be modeled with a fixed base, and the support reactions will be found. The model will be set up a little bit differently from the previous models: the supports will induce a moment on the panels to keep them flat at the point where they connect. However, this is just for ease of modeling, and this setup will induce the same moment on the support legs and will ease modeling a little bit. This means that that stress that the model shows on the panel will be slightly higher than was previously shown, but the stress on the solar panels will not be used, just the support forces at the base of the supporting beams. After the support reactions are found, they will be used to solve for a constant to linearly vary the stresses with v_{wind}^2.

Below is a picture of the finite element model of the entire solar panel assembly:

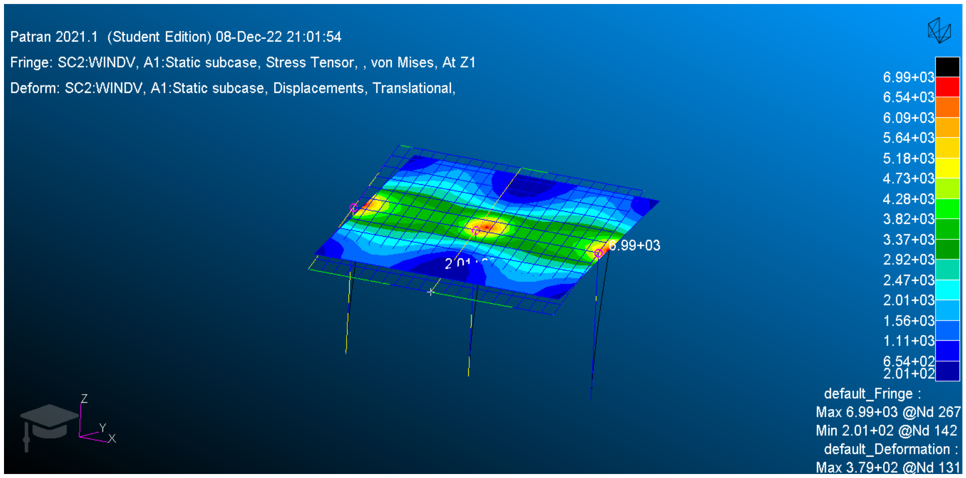


Figure 11: Overall Stress in the Full Model

The fringe on the right shows stress in psi, and the maximum deformation at this setup is 379 in at the center of the top of the solar panel. Obviously, this deformation would break the solar panel, but it still provides data to solve for the constant in equation 8. The model shows the following support reactions with respect to the coordinate system shown in the bottom left of figure 10:

	Left Support	Middle Support	Right Support
Moment in x (lb-in)	$1.89*10^7$	$1.89*10^7$	$1.89*10^7$
Moment in y (lb-in)	$3.03*10^4$	0	$-3.03*10^4$
Moment in z (lb-in)	$-1.77*10^4$	0	$1.77*10^4$
Force in x (lb)	$3.79*10^2$	0	$-3.79*10^2$
Force in y (lb)	$-7.85*10^4$	$-7.88*10^4$	$-7.85*10^4$
Force in z (lb)	$2.6*10^4$	$1.8*10^5$	$2.6*10^4$

Table 1: Support Reactions at Each Support Leg

To find Von Mises Stress, the first step is to find the stresses of a 3D element. On the center bar, the stress at the highest stress point is: $\sigma_z = -1{,}420\ \text{k}si, \tau_{yz} = 14.6\ \text{k}si$. The stress state on the left bar is $\sigma_z = -1{,}395\text{k}si, \tau_{xz} = 907psi, \tau_{yz} = 14.6\ \text{k}si$. This yields a Von Mises Stress of 142,000 ksi for the center bar, and a 1,395ksi Von Mises Stress for the left and right bar by symmetry. This shows that the Von Mises Stress is going to be the same as σ_z due to the other stresses being many orders of magnitudes smaller. This means that the Von Mises Stress is very close to $\frac{F_z}{A} + \frac{M_x c}{I}$, with the bigger Von Mises stress being on the center bar. Due to the stiffness of the solar panels staying the same, $\frac{F_{z,\text{Center}}}{F_{z,\text{Outer}}} = 6.92$ will stay constant, with $2F_{z,\text{Outer}} + F_{z,\text{Center}} = F_{z,Total}$. This implies the following:

$$F_{z,\text{Center}} = .776F_{z,Total}(9)$$

To solve for what the moment, M_x, will be on the center bar, a similar procedure will be followed, but since M_x is the same across the bars, $M_x = .333M_{total}$

$$\Rightarrow M_x = .333 * \left(14 + 12.3sin(\theta)\right) * 12 * F_{y,total}(10)$$

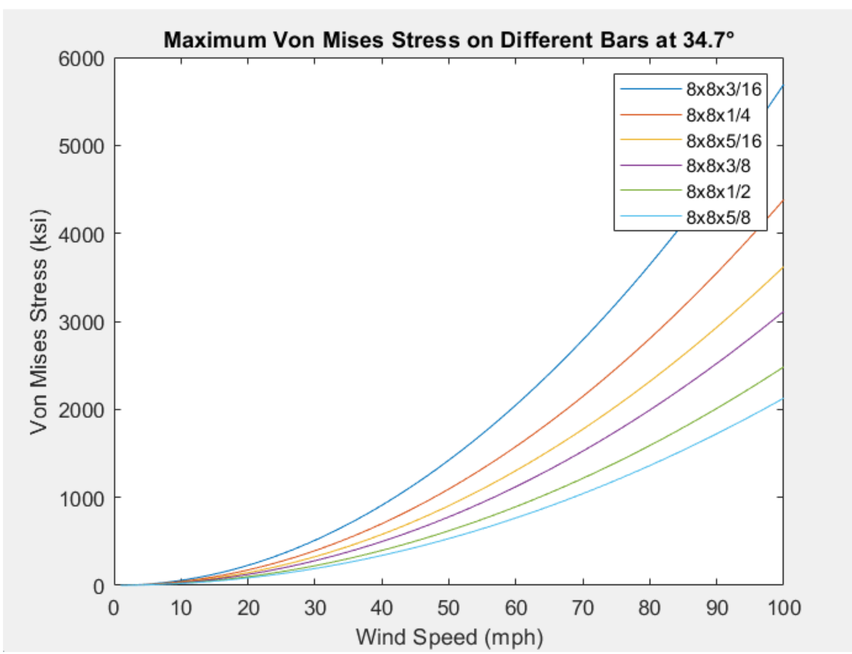
This is because to maintain the level of clearance of 14 feet, the length of the supports will be adjusted as the angle of tilt changes. This means that the overall Von Mises Stress for every load is:

$$\sigma_{VM} = \frac{.776F_{z,Total}}{A} + \frac{\left(14 + 12.3sin(\theta)\right) * 12 * F_{y,total}{}^{*}c}{3I} (11)$$

Where $F_{z,Total}$ is lift and $F_{y,total}$ is drag as calculated before.

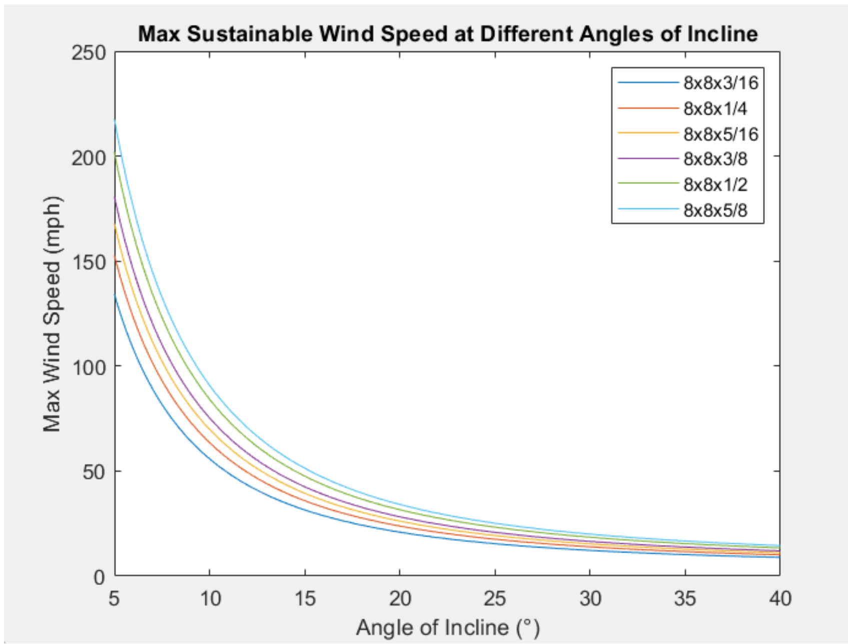
This has been verified across various load ranges to ensure that the large deflection of the 50mph scenario was not affecting the results.

Since the correlation between bar specifications, angle of incline, and bar has been made using FEA, it is able to be plotted:



Since the yield strength of steel is 60 ksi, this angle is not valid for this project for any wind speeds very high. For the strongest beam, 8x8x5/8, the maximum wind speed is 16.8mph to

before it reaches 60 ksi. The following graph will show what the maximum wind speed for each bar and every angle:



This shows that above 6.4° of incline, even the strongest beam cannot support wind speeds above 100 mph.

Conclusion

At 6°, the solar panel itself reaches 547 lb-in and breaks under a 100 mph wind load, and at 6.4°, even if the solar panel did not break before it, the supports reach the yield strength of 60 ksi on the base of the supports. The beam to support the solar panels as shown in the picture is way too weak to support normal wind activity, and it should be upgraded to something bigger than 8” across. The solar panels also show poor design, as the support beams that go across them are relatively big, but the slight deflection in the supports breaks the glass over the solar panels. Decreasing the angle of incline to something smaller like 5° would protect the investment with a

small factor of safety, but it could sacrifice efficiency in the solar panels as shown in the previous part to this project. Very small improvements in the design of this part could mean drastic improvements in structural integrity, and they should be made. In the pictures of the solar panel canopy that are shown on the website, they are all at an angle much smaller than the 34.7° that is most efficient at least in Huntsville. The results were unexpected, and the improvements suggested should be made.

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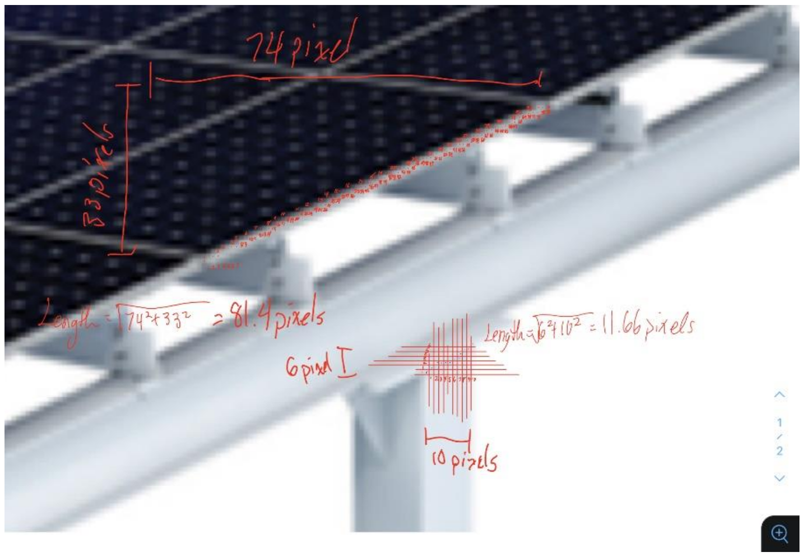
Appendix



Appendix 1: Counting the Pixels on the Solar Panel

```
function M=moment(speed,ang) %speed in mph, ang in degrees
    F=findF(speed,ang);
    angle=90-acos(dot(plane,F)/(norm(plane)*norm(F)))*180/pi;
    Pressure=norm(F)/144*sind(angle);
    M=Pressure*295.2*236/2/2*236/2;
end
function F=findF(speed,ang) %F outputs per ft^2
    v=speed*1.4667;%speed in mph to ft/s
    a=ang*pi/180;
    Cdo=1.28*sin(a);
    Clo=2*pi*a;
    A=7.5*6*3.28^2*sin(a); %just the area perpendicular to flow
    AR=19.68^2/A;
    Cl=Clo/(1+Clo/(pi*AR));
    Cd=Cdo+Cl^2/(.7*pi*AR);
    rho=.0765; %lb/ft^3
    Fadrag=.5*rho*Cd*(v.^2)*sin(a);
    Falift=Cl*sin(a)*rho*(v.^2)/2;
    plane=cross([0 20.22 14],[19.68 0 0]);
    F=[0 Fadrag -Falift];
```

Appendix 2: Functions Used

```
function vm=findVM(Speed,Ang,area,I)
    Force=findF(Speed,Ang);
    Force=Force*19.68*24.6*2;
    vm=.776*Force(3)/area;
    vm=vm+((14+12.3*sind(Ang))*12*Force(2)*4)/(3*I);
    vm=vm/1000;
end
function v=FindMaxSpeed(angle,area,I)
    v=0;
    while 60>findVM(v,angle,area,I)
        v=v+.1;
    end
end
```

Appendix 3: More Functions Used

Honors Capstone:

Solar Panel Canopy Stress Analysis

By Terrell Elias Marler

December 9th, 2022

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Abstract

This project intends to investigate the efficacy of solar panel canopies over Walmart parking lots in multiple parts of the US. The previous section to this project showed profitability, but this section intends to show physical stability of the structure through different types of wind loads on the solar panels themselves. The solar panels will be high into the air above where the cars would theoretically be, and therefore, they will be exposed to high wind loads on the foundation and on the supporting rod that will be holding the solar panels up. Because different parts of the country have different peak wind speeds such as frequent hurricanes coming through the southern states, there will be different loads on the supporting beams. This project will use hand-validated finite element analysis to look at the previously selected product called SunPower Helix T-Type Carport and do structural analysis to check how different wind loads affect the stresses created in the carport.

Introduction

As the need for power grows with industries like Tesla, Amazon, and Meta, the demand from the market for power generation grows with it. However, with increasing pressures from society to be carbon neutral or carbon negative, solar panels are a great approach. Many companies today purchase land specifically for solar panels, but with the increasing real estate costs in Huntsville and the surrounding areas, it is becoming less and less cost effective to buy the land. However, there is an area of land that every company, small business owner, and even local household owns: parking spaces.

It may be relatively easy to construct a small roof over their parking spaces, and the benefits would be twofold: it would generate electricity for selling back to the grid or using at their building, and it would be shade for the cars that needed to park underneath. Selling the electricity to the grid or using it to power their buildings would increase profits month to month, and it would certainly have a huge impact as time goes on. Additionally, with the high temperatures in the South, people try to park in the shade so that their air conditioning does not have to run on full blast for the first few minutes when their car inevitably heats up after hours of parking in the sun. A common idea for people in the heat would be to park under a tree as this solves the problem. The issue with this is that it drops sap, bird droppings, and leaves on an individual’s car. This would solve every problem with parking.

With carbon taxes growing around the world, having a system to reduce emissions would be extremely beneficial for the bottom line. As of 2021, there are 35 carbon taxes around the world, and as they are mostly in developed countries, there will likely be a carbon tax introduced in the US soon. Especially in state law, carbon taxes are already passed in several states, making

it more difficult to keep within profitable margins for certain companies that were used to emitting massive amounts of carbon without repercussions.

Additionally, with high speeds from hurricanes that have happened recently in the Gulf of Mexico and the Atlantic into states like Louisiana, South Carolina, and North Carolina, a future investor would want to make sure their investment will last for the full period that it would take to pay off: about 15-25 years in the cases tested. If a Category 2 hurricane comes in with 100 mph winds, the owner would want to make sure their massive investment is not going to become worthless. Especially if a bigger hurricane comes through, there could be massive losses. Every year, millions and billions of dollars are lost due to structures breaking in high wind speeds, and this project will determine whether the canopy will be one of them.

With these reasons and the previously shown financial viability, there are many reasons to move towards a solar panel parking lot canopy. However, there is uncertainty that the structure will stay stable through all kinds of conditions. This project will use several assumptions: the foundation of the canopy itself will remain stable, the supports and bolts are made of steel, and that the only forces from the wind on the panels are lift and drag. This will use finite element analysis using Patran and Nastran to find maximum Von Mises stress all the way through the model.

Methodology

The first step is to find the dimensions of the parts of the supports and the solar panel canopy. It is documented that the canopies use SunPower 450W 22.2% Efficient Panels. These

panels are documented have 72 cells in a 5 by 16 setup. Each cell is 125 mm by 125 mm. This means that each panel is .75 m by 1.5 m. The SunPower T-Type Carport is 15 x 5 solar panels for overall dimensions of 12 m by 7.5 m (SunPower). The SunPower Helix Carport is adjustable between 10-14 feet high. However, as the standard 18-wheeler is 13.6 feet tall, it can be assumed that the average owner of a Walmart would opt for the 14 foot or 4.27 meter tall option at installation. As discussed in the previous report, the ideal angle that the solar panels would be tilted at would be 34.7° south towards the equator.

The solar panel itself (excluding the supports) is documented to have been tested in 2018 to support a maximum moment of 574 kip-in in the beams running across the bottom of the panels. Below is an image of the solar panels in the stress analysis before fracture (Bapat).

Figure 1: Screenshot Deflection Test on Panels (Bapat)

The documented load at failure is very small compared to what could be generated from the wind. This means that a potential point of failure is at the solar panels themselves. The method of failure seems to not be in the beams going across the bottom of the panels, but in the panels themselves, as can be seen in the video. The flexing of the of the bar caused the panels to

break. The moments on the panels from wind will be calculated by hand and plotted as a function of wind speed. Then, at a wind speed of 100mph, an finite element model will be created in Patran and analyzed in Nastran to verify the hand calculations and validate the model for the whole spectrum of speeds.

After the maximum speed is calculated for the solar panel itself, it is necessary to figure out if the supporting beam that goes from the solar panels into the foundation will fail before the solar panel itself. The solar panels will initially be created, and then it will be attached to the rest of the model for further evaluation. If the model with everything attached gets to the yield strength of steel before the solar panels break, the failure point will not be the panels themselves.

The peak wind speeds recorded in a year period around the country as shown below range from 62 to 98 mph. This means that any solar panel canopy designed should be able to withstand wind speeds of above 100 mph at least. If a hurricane came through with even faster wind speeds, the design necessary will be shown in charts to be able to withstand any wind speed one could need.

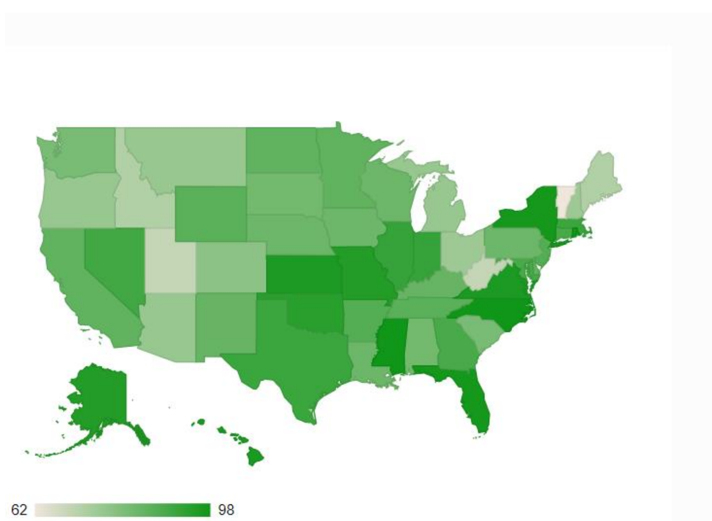

Figure 2: Map of Peak Wind Speeds across the US (Climatic Wind Data)

Calculations

Using the documented failure moment on the canopy, a 2D distributed load will be placed on top of the solar panels from the wind to see at which wind speed the solar panels will break. Below is the picture of the solar panels:

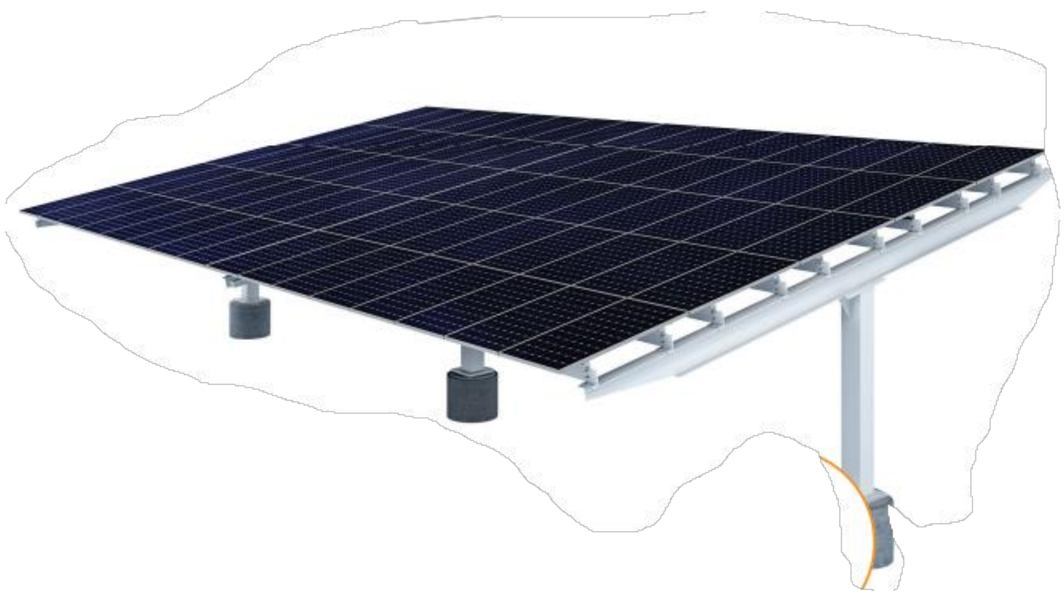

Figure 3: SunPower T-Type Solar Canopy (SunPower)

To make modeling of just the solar panels easier, the canopy will be simplified to just be one of the sides, with supports on either side. This means that only from the middle support to the right will be used in the modeling. From the middle over is 236 inches by 295.2 inches The longer edge is the one with the supports.

To find the wind speeds, the NASA documentation on kites will be used (Kite Drag Equations & Kite Lift). So, the flat plane at an incline will be modeled as a kite to ease calculations. The lift is the force from the wind perpendicular to the flow direction, and the drag

is the force parallel to the flow direction. The flow is assumed to be flowing directly into the panels. The necessary equations are:

$$C_{lo} = 2\pi a, where\ a\ is\ the\ angle\ of\ incline, 34.7\ degrees\ or\ .6056\ radians\ (1)$$

$$C_l = \frac{C_{lo}}{1 + \frac{C_{lo}}{\pi AR}}, where\ AR\ is\ the\ aspect\ ratio\ (2)$$

This means that $C_{lo} = 2\pi * .6056$=3.81, and C_l=2.04. C_l is the coefficient of lift.

Next, the coefficient of drag, C_d, needs to be found.

$$C_{do} = 1.28sin(a)\ (3)$$

$$C_d = C_{do} + \frac{C_l^2}{.7\pi AR}\ (4)$$

This means that $C_{do} = 1.28sin(34.7) = .729$, and $C_d = .7287 + \frac{2.04^2}{.7\pi*1.4} = 2.08$

To convert from coefficient of drags and lifts, the following equations are used:

$$F_{drag} = C_d A\rho \frac{V^2}{2}, where\ \rho \text{ is the density of the air } (5)$$

$$F_{lift} = C_l A\rho \frac{V^2}{2}\ (6)$$

The density of air that will be used is $.0765\ lb/ft^3$ (Will V).

The air speed of 100 mph will be used in the finite element model, and the hand calculations at this speed will be compared to the finite element.

The values found is $F_{drag} = 472kip$, and $F_{lift} = -463kip$. This is evenly distributed across the panels. This means that the angle of the net force on the solar panels is 79.2 degrees, almost perpendicular. The forces are close enough to perpendicular that the hand calculations will initially be modeled as a pressure acting perpendicular to the panels, and the force used will be: $|F|sin(79.2) = 650\ kip$, evenly distributed across the panels. The finite element model will have two load cases, one with the pressure to compare to the hand calculations, and one with the force as the vector it actually is to compare to the other answers. A diagram to better visualize the project is below with the red arrows being the support reactions:

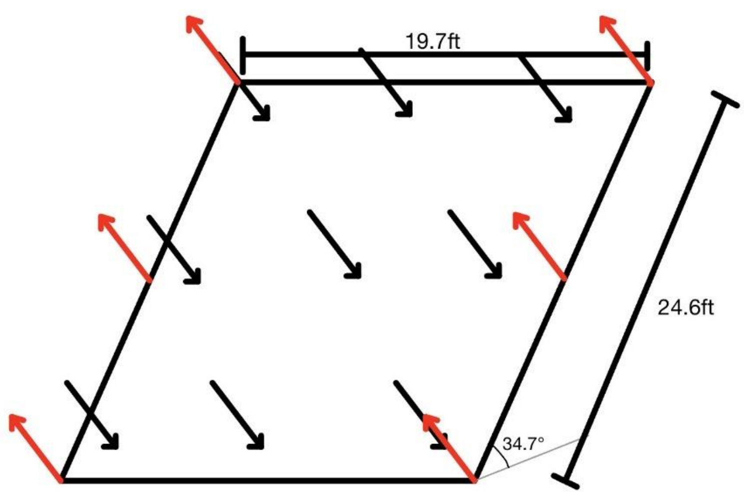

Figure 4: Distributed Force Diagram

This can be simplified to a distributed load:

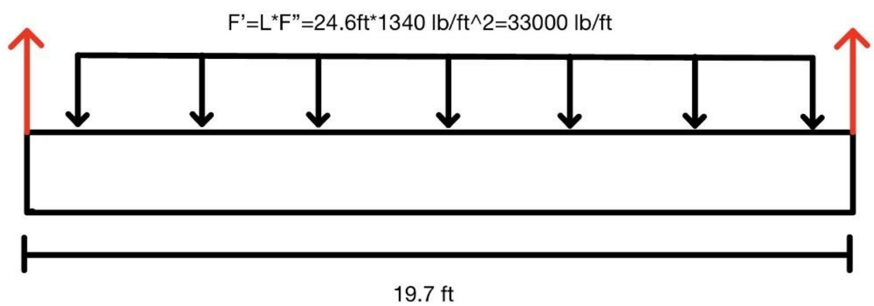

Figure 5: Distributed Load on Panel

From this, shear and moment diagrams can be created:

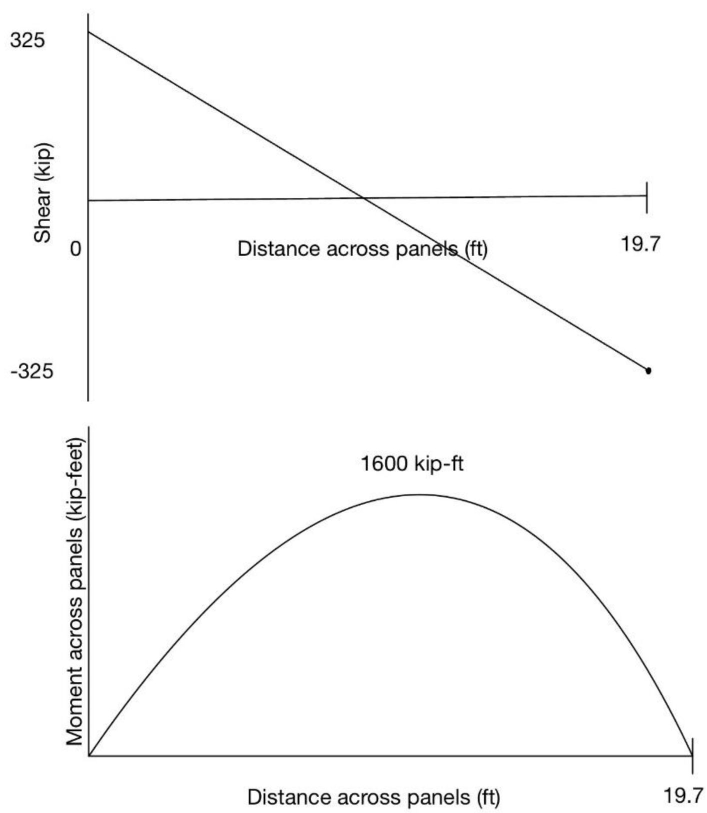

Figure 6: Shear and Moment Diagrams across Panel

The parabolic shape of the moment diagram shows a peak halfway through the shape with a peak moment of 1600 kip-feet or 19,200 kip-in. To verify these calculations, finite element analysis is

done. Below is a picture of the Von Mises stress and deformations of purely the component of the force that is normal to the panel.

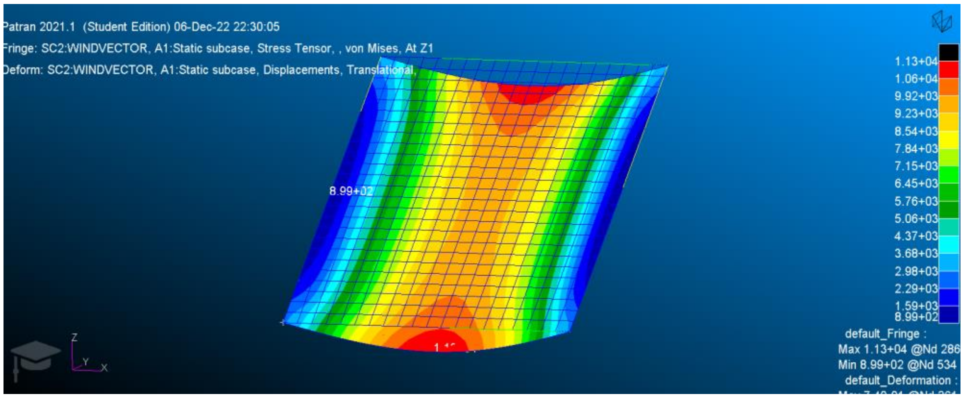

Figure 7: FEM Output with only Normal Pressure

Because other forces are present, the total load vector was also used, but these will not be compared to the hand calculations. Because these include slightly different and higher force vectors, the stress is slightly higher in the version done with total force vector:

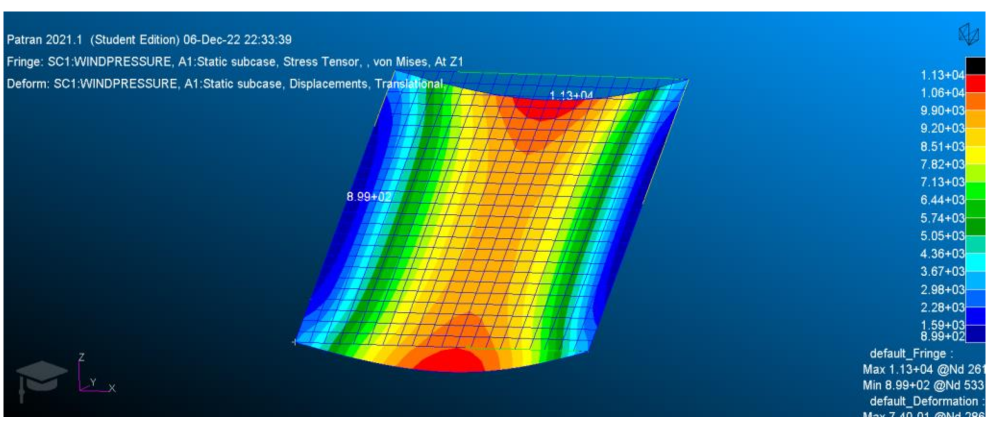

Figure 8: FEM with Force as a Vector

The fringe on the right is stress in psi. It can be seen that the average stress across the center of the panel on the first graphic is about $9.5(10)^3$ psi. However, these stress values do not mean very much. This is because to get an output on Nastran, a thickness of the sheet needed to

be entered. This is because Nastran does not calculate moment and shear diagrams, but stress for each element. The thickness entered was 6”. To obtain the moment at that point, the stress and dimensions of the sheet can be used using the following formula:

$$\sigma = \frac{Mc}{I} \quad (7)$$

$$\Rightarrow \mathrm{M} = \frac{\sigma \mathrm{I}}{\mathrm{c}}$$

Where c is the distance from the neutral axis, I is the area moment of inertia, and σ is the stress.

For a beam that is 24.6 feet by 6 inches, the moment of inertia is $\frac{1}{12}bh^3 = 5313.6in^4$. $c = 3''$ because the stress at the outside of the beam is what is important. So, the moment is $9.5(10)^\wedge 3 * 5313.6/3 = 16{,}800\ kip - in.$ This is a 14% error from the hand calculations, but due to the wide ranges of stresses over the center of the beam and selecting a general average, the 14% error is expected. This validates the model used in the hand calculations, and it will be used to create a curve of maximum moment across all speed ranges of the wind. Below is the

graph of that information with a second curve denoting the maximum sustainable moment in the solar panels.

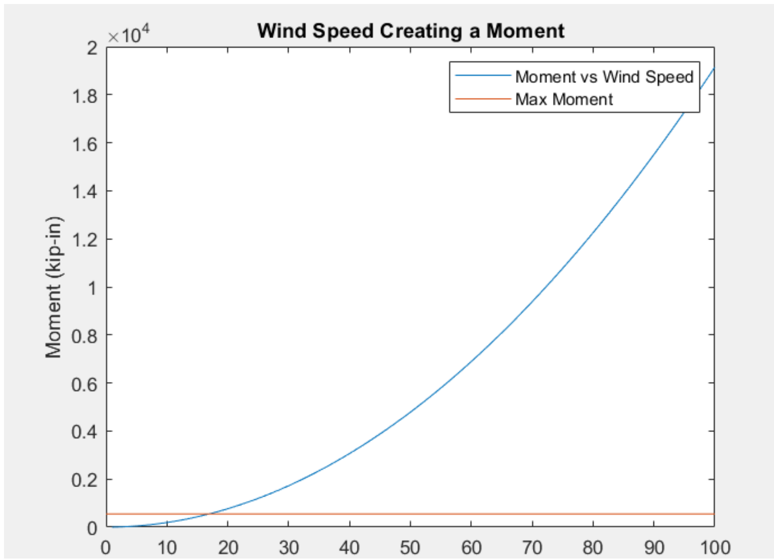

Figure 9: Graph Showing Moment at Different Wind Speeds

The intersection of the actual moment against the maximum sustainable moment is at 16.9 mph. This means that the failure point of the panels is when wind at 16.9 mph hits the panels. Once again, the failure point was not the beams supporting the panels, but the deflection in the beams causing the panels to hit against each other and breaking. This is poor design.

However, changing the angle of the solar panels can affect the maximum wind speed that the panels are able to sustain. The maximum speed at 34.7° is 16.9 mph, but at the expense of

efficiency of the panels, the maximum speed can be increased. Below is a graph of the maximum speed that the panels can sustain at each angle of incline:

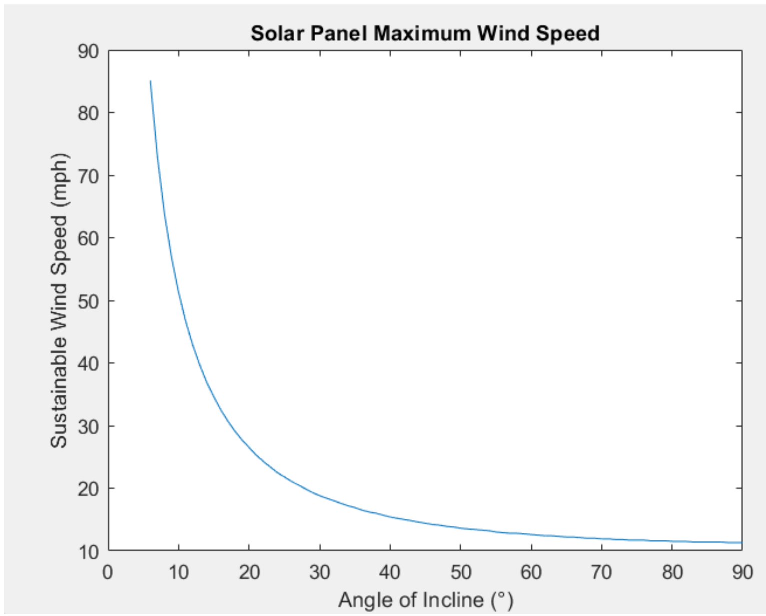

Figure 10: Graph Showing Max Wind Speed at Each Angle of Incline

The wind speed gets very high as the angle of incline decreases. Values over 100 mph were deleted as they will not be necessary for the results. This means that the first viable angle of incline is 6°.

The next step in the calculations is to calculate how much stress is created in the support beams themselves. These are the beams that support the solar panels from the ground. As discussed above, the beams must be tall enough to create 14 feet of clearance from the ground from the bottom of the solar panel. This means that as the angle of the solar panel increases, the height of the supports must be adjusted. Once again, hand calculations will be made, and they will be verified for a certain value using the finite element software Patran and Nastran.

The first step is to find the dimensions of the beam that supports the solar panels from the ground. This will be done using pixel counting. Using pixel counting and the Pythagorean Theorem on Figure 2, it can be shown that the supporting beam is a square hollow section with dimensions 8”x8” (Appendix 1). However, it is not clear how thick the walls are. The different area moment of inertias for this beam shape is listed on Engineering Toolbox, and they range from 146 in^4 for a 5/8” thick wall to 54.4 in^4 for a 3/16” thick wall. To start, the conservative 54.4 in^4 will be used in calculations and FEA modeling. If it appears that the beam will yield, a higher moment of inertia can be used.

To calculate the reaction forces at the base of the supports, the finite element model will be used at 50mph. Because there are three support reactions, one from each beam, and all in a line, this setup is statically indeterminate, and the model will be used to figure out what will happen at each of the support reactions. The solar panels will once again be modeled using 6” thick steel 2D elements, with a Young’s Modulus of $30(10)^6$ psi and a Poisson’s Ratio of .3. The support beams will be modeled with a fixed base, and the support reactions will be found. The model will be set up a little bit differently from the previous models: the supports will induce a moment on the panels to keep them flat at the point where they connect. However, this is just for ease of modeling, and this setup will induce the same moment on the support legs and will ease modeling a little bit. This means that that stress that the model shows on the panel will be slightly higher than was previously shown, but the stress on the solar panels will not be used, just the support forces at the base of the supporting beams. After the support reactions are found, they will be used to solve for a constant to linearly vary the stresses with v_{wind}^2.

Below is a picture of the finite element model of the entire solar panel assembly:

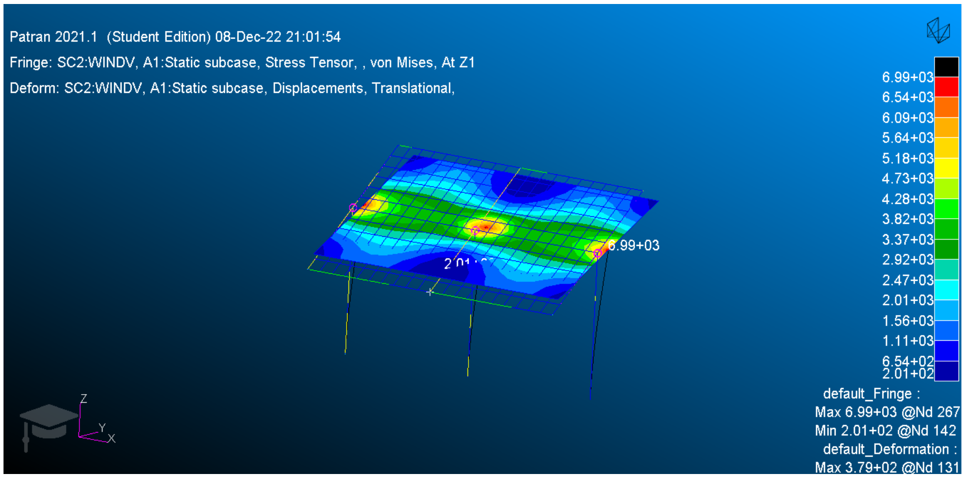

Figure 11: Overall Stress in the Full Model

The fringe on the right shows stress in psi, and the maximum deformation at this setup is 379 in at the center of the top of the solar panel. Obviously, this deformation would break the solar panel, but it still provides data to solve for the constant in equation 8. The model shows the following support reactions with respect to the coordinate system shown in the bottom left of figure 11:

	Left Support	Middle Support	Right Support
Moment in x (lb-in)	$1.89*10^7$	$1.89*10^7$	$1.89*10^7$
Moment in y (lb-in)	$3.03*10^4$	0	$-3.03*10^4$
Moment in z (lb-in)	$-1.77*10^4$	0	$1.77*10^4$
Force in x (lb)	$3.79*10^2$	0	$-3.79*10^2$
Force in y (lb)	$-7.85*10^4$	$-7.88*10^4$	$-7.85*10^4$
Force in z (lb)	$2.6*10^4$	$1.8*10^5$	$2.6*10^4$

Table 1: Support Reactions at Each Support Leg

To find Von Mises Stress, the first step is to find the stresses of a 3D element. On the center bar, the stress at the highest stress point is: $\sigma_z = -1{,}420\ ksi, \tau_{yz} = 14.6\ ksi$. The stress state on the left bar is $\sigma_z = -1{,}395 ksi, \tau_{xz} = 907 psi, \tau_{yz} = 14.6\ ksi$. This yields a Von Mises Stress of 142,000 ksi for the center bar, and a 1,395ksi Von Mises Stress for the left and right bar by symmetry. This shows that the Von Mises Stress is going to be the same as σ_z due to the other stresses being many orders of magnitudes smaller. This means that the Von Mises Stress is very close to $\frac{F_z}{A} + \frac{M_x c}{I}$, with the bigger Von Mises stress being on the center bar. Due to the stiffness of the solar panels staying the same, $\frac{F_{z,Center}}{F_{z,Outer}} = 6.92$ will stay constant, with $2F_{z,Outer} + F_{z,Center} = F_{z,Total}$. This implies the following:

$$F_{z,Center} = .776 F_{z,Total} (9)$$

To solve for what the moment, M_x, will be on the center bar, a similar procedure will be followed, but since M_x is the same across the bars, $M_x = .333 M_{total}$

$$\Rightarrow M_x = .333 * \left(14 + 12.3 sin(\theta)\right) * 12 * F_{y,total} (10)$$

This is because to maintain the level of clearance of 14 feet, the length of the supports will be adjusted as the angle of tilt changes. This means that the overall Von Mises Stress for every load is:

$$\sigma_{VM} = \frac{.776F_{z,Total}}{A} + \frac{\left(14 + 12.3sin(\theta)\right) * 12 * F_{y,total} * c}{3I} \quad (11)$$

Where $F_{z,Total}$ is lift and $F_{y,total}$ is drag as calculated before.

This has been verified across various load ranges to ensure that the large deflection of the 50mph scenario was not affecting the results.

Since the correlation between bar specifications, angle of incline, and bar has been made using FEA, it is able to be plotted:

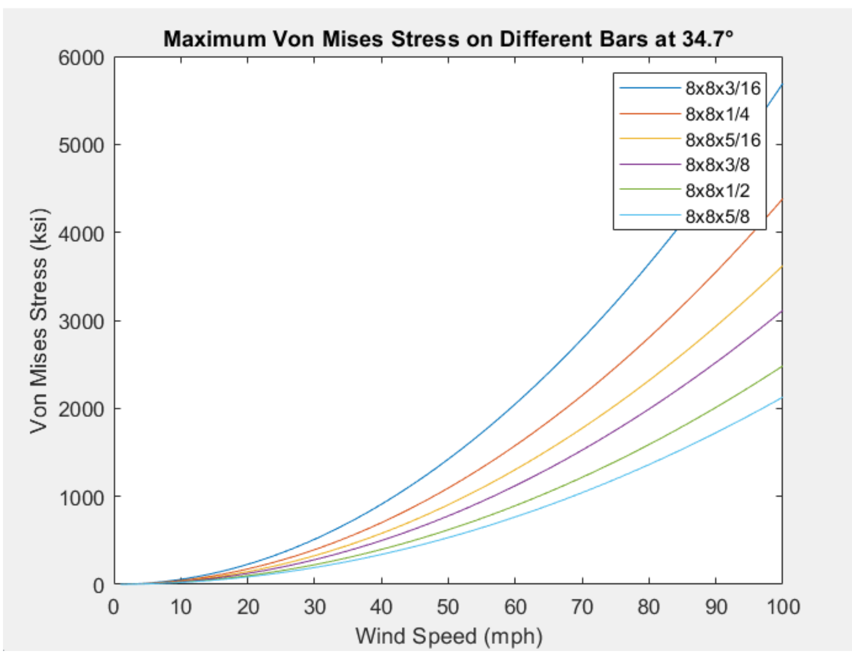

Figure 12: Max Stress in Supporting Beams at 34.7° Plotted against Wind Speed

Since the yield strength of steel is 60 ksi, this angle is not valid for this project for any wind speeds very high. For the strongest beam, 8x8x5/8, the maximum wind speed is 16.8mph to

before it reaches 60 ksi. The following graph will show what the maximum wind speed for each bar and every angle:

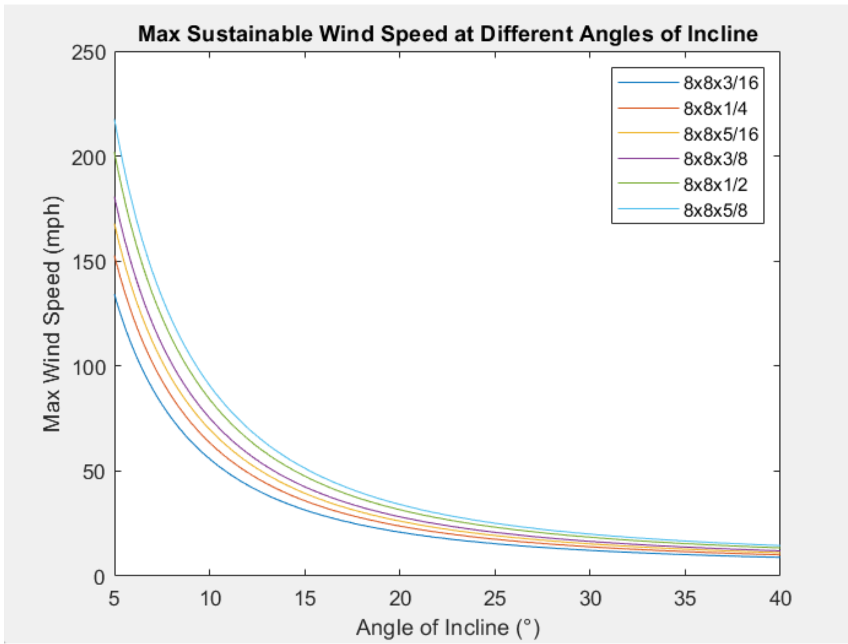

Figure 13: Max Wind Speed for Different Angles of Incline

This shows that above 6.4° of incline, even the strongest beam cannot support wind speeds above 100 mph.

Conclusion

At 6°, the solar panel itself reaches 547 lb-in and breaks under a 100 mph wind load, and at 6.4°, even if the solar panel did not break before it, the supports reach the yield strength of 60 ksi on the base of the supports. The beam to support the solar panels as shown in the picture is way too weak to support normal wind activity, and it should be upgraded to something bigger than 8" across. The solar panels also show poor design, as the support beams that go across them are relatively big, but the slight deflection in the supports breaks the glass over the solar panels.

Decreasing the angle of incline to something smaller like 5° would protect the investment with a small factor of safety, but it could sacrifice efficiency in the solar panels as shown in the previous part to this project. Very small improvements in the design of this part could mean drastic improvements in structural integrity, and they should be made. In the pictures of the solar panel canopy that are shown on the website, they are all at an angle much smaller than the 34.7° that is most efficient at least in Huntsville. The results were unexpected, and the improvements suggested should be made.

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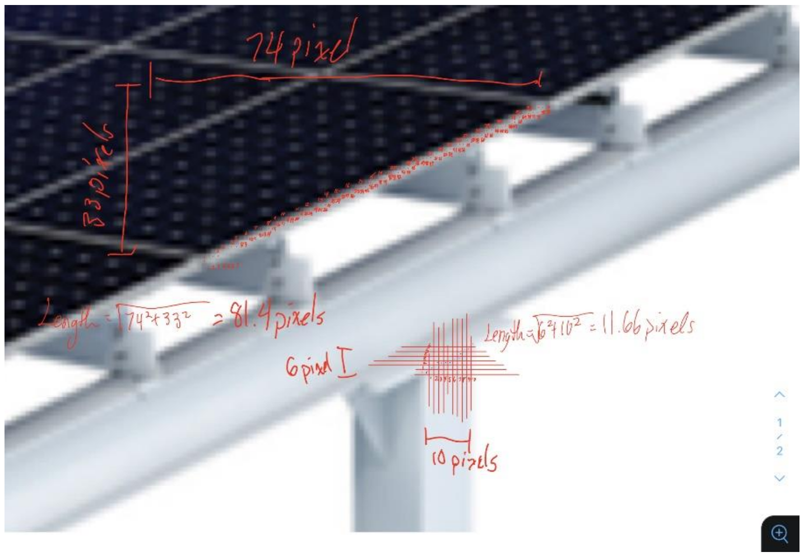
Appendix



Appendix 1: Counting the Pixels on the Solar Panel

```
function M=moment(speed,ang) %speed in mph, ang in degrees
    F=findF(speed,ang);
    angle=90-acos(dot(plane,F)/(norm(plane)*norm(F)))*180/pi;
    Pressure=norm(F)/144*sind(angle);
    M=Pressure*295.2*236/2/2*236/2;
end
function F=findF(speed,ang) %F outputs per ft^2
    v=speed*1.4667;%speed in mph to ft/s
    a=ang*pi/180;
    Cdo=1.28*sin(a);
    Clo=2*pi*a;
    A=7.5*6*3.28^2*sin(a); %just the area perpendicular to flow
    AR=19.68^2/A;
    Cl=Clo/(1+Clo/(pi*AR));
    Cd=Cdo+Cl^2/(.7*pi*AR);
    rho=.0765; %lb/ft^3
    Fadrag=.5*rho*Cd*(v.^2)*sin(a);
    Falift=Cl*sin(a)*rho*(v.^2)/2;
    plane=cross([0 20.22 14],[19.68 0 0]);
    F=[0 Fadrag -Falift];
```

Appendix 2: Functions Used

```
function vm=findVM(Speed,Ang,area,I)
    Force=findF(Speed,Ang);
    Force=Force*19.68*24.6*2;
    vm=.776*Force(3)/area;
    vm=vm+((14+12.3*sind(Ang))*12*Force(2)*4)/(3*I);
    vm=vm/1000;
end
function v=FindMaxSpeed(angle,area,I)
    v=0;
    while 60>findVM(v,angle,area,I)
        v=v+.1;
    end
end
```

Appendix 3: More Functions Used